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CERAMIC CLAY IN HAWAII

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¹ Chemical analyses and discussion published with approval of the Director, U. S. Geological Survey.

INTRODUCTION

PURPOSE AND SCOPE OF STUDY

Exceptional interest, from the standpoint of the geologist, the student of soils, and the practical craft potter, attaches to the recent discovery of excellent ceramic clay in Hawaii. This clay was first found in 1935, in small deposits in restricted areas near the crest of the Koolau Range of eastern Oahu. A considerable amount of high-grade pottery has been made of clay from this area by members of the Hawaiian Potters' Guild during the past three years. It has been supposed that clay would be found in topographically similar situations on other islands and some samples had been sent to Honolulu. In the summer of 1938, Wentworth collected samples and made brief examinations of clay localities on East Molokai, West Maui and Kauai. In this paper the occurrence and geologic relations of the clay are described by Wentworth, the chemical analysis and discussion are by Wells and the petrography and mineralogy by Allen. In addition, in order to define more accurately the ceramic character of the Hawaiian clay, a few practical tests of physical properties have been made. These have been applied to the three clays used by the Hawaiian Potters' Guild, in order to refer to two clays known in the United States. They also furnish in the practical work of guild members, some rational explanation of the behavior of the clays, which is already familiar from practical experience.

SIGNIFICANCE AND HISTORY OF CERAMIC MATERIALS IN HAWAII

It is a well-established fact that there was no ceramic art among native Polynesian peoples in the central Pacific area, to which Hawaii belongs. This is an area of true oceanic islands, which are chiefly basaltic, or coral islands, and a region where continental types of rocks, such as coal, clay, plutonic rocks, ores of metals, and the like, are generally absent. It stands in contrast to the islands of probable continental affinities, which lie south and west from Fiji, (Fig. 1), in some of which pottery making was known to primitive races. This fact, and the underlying geologic and climatic basis, gives special interest to the clay here described.

Soft, gumbo-like soil material is by no means rare in Hawaii, but nearly all such material is either highly ferruginous or contains other constituents detrimental to ceramic use. Light-colored muds are found on parts of the coastal plain, but these have not shown ceramic quality and probably carry excessive amounts of calcium carbonate. Dark gray, nearly black alluvium, colloquially known as "taro-patch clay" is common on the flats of larger valley bottoms, but, so far as known,

none of this material can be used successfully for making pottery. In places volcanic ash of basaltic composition, or such material altered to palagonite, has been further decomposed into a soft, unctuous mass, red or brown in color, having some physical features that resemble bentonite. Some of these materials have been used with other clays in developing

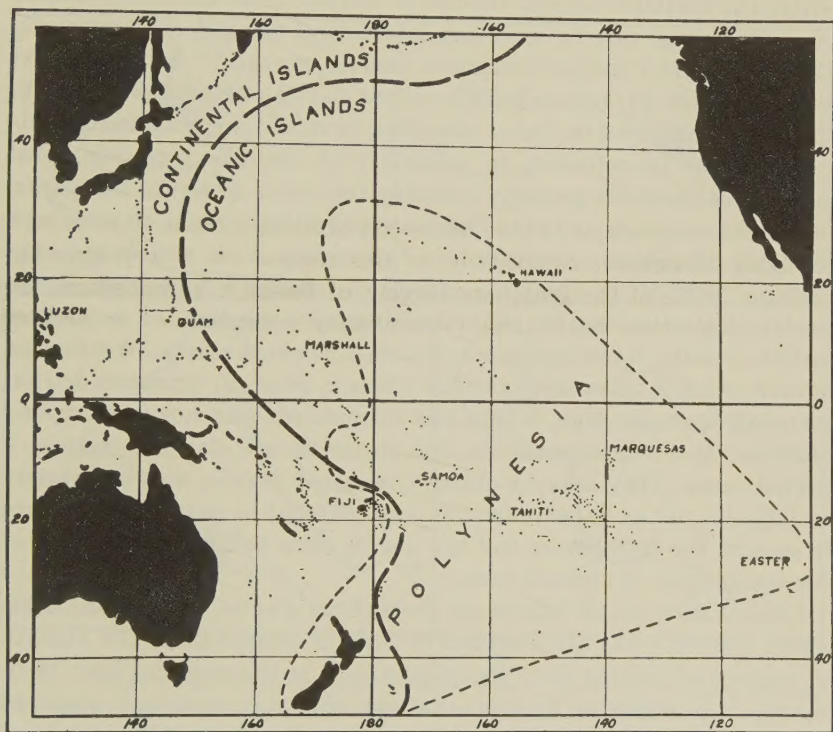


FIG. 1. Map of Pacific Ocean showing distribution of islands and boundary between islands having continental types of rocks, and those lacking such rocks and composed only of basic volcanic rocks, or of coral and related sediments.

distinctive colors in pottery, but these used alone are not suitable for ceramic use.

From the beginning of settlement of westerners in Hawaii there has been sporadic search for clay material either suitable for ceramic use, or usable as an aluminous constituent in the making of Portland cement. Ocean freight rates constitute a differential which would strongly favor the establishment of brick, tile or cement plants in Hawaii if raw materials reasonably suitable for these products could be found. Experiments have been made by several persons looking to local production,

both of brick and cement, but with no substantial success to date. During the period 1917–1922, when the World War led to unfavorable ocean freight conditions, a hydraulic cement was made on the island of Maui. Soda trachyte from Launiopoko Hill near Lahaina was used as the source of silica and alumina, and the resulting cement was in most respects within the Portland cement standards. Certain differences necessitated more than usual care by workmen in practical use and the project was abandoned when freight conditions became normal.^{2,3} Attempts have also been made to produce brick from red clays on Maui, but these, like similar projects tried on Oahu, according to report, were not successful.³

Frequently consulted as to suitability of clay-like materials, most students of Hawaiian geology, including the senior author of this paper, have been skeptical as to the likelihood of finding ceramic clays or rock of highly aluminous composition in this region. As is well known, the volcanic rocks of the group are largely of basaltic composition, dominantly plagioclase basalts, but subordinately nepheline, or nepheline-melilite basalts. A few trachyte or andesite flows are known. Weathering of such rocks, in an oceanic, tropical climate, generally produces detrital materials and soils high in iron and magnesium, and low in silica and alumina. As a consequence the soil materials are clay-like only in a partial sense. They may be sticky, somewhat plastic, and moderately suitable for use as impervious core-wall material in dams, but they are in general too ferruginous and too low in silica and alumina to dry or fire successfully in ceramic tests.

Clay is rare on all islands of the central Pacific (Polynesia) area, where igneous rocks are dominantly basic in composition. The absence of ceramic art among the Polynesian people in this area has been mentioned. It is suggested by some that use of pots in cooking is rendered unnecessary by the general practice of steam cooking of leaf-wrapped food in a ground oven (Hawaiian *imu*), but the possibility of a reciprocal development of such cooking as a result of the lack of pottery is worth consideration.

DISCOVERY OF LOCAL DEPOSITS OF CLAY

Under the auspices of the Honolulu Academy of Arts for several years past, and to a limited extent in certain schools, craft pottery has been taught. About 1931, Mrs. James A. Wilder started classes in craft pottery at the Honolulu Academy of Arts. More recently this work has been expanded under the supervision of Mrs. Nancy Andrew and has led to the formation of the Hawaiian Potters' Guild. Enthusiasts in the craft,

² Foster, J. P., Personal communication.

³ Watkins, W. K., Letter dated August 23, 1937.

despite geological skepticism, have continued the search for ceramic clay on Oahu. In 1934, near the crest of the Koolau Range, a light-gray (in places almost white) clay was found, which gave very promising results on testing. The find was made by Lieut. Thomas Wells and Mr. Joseph Musser. Since that time additional sites have been found and in

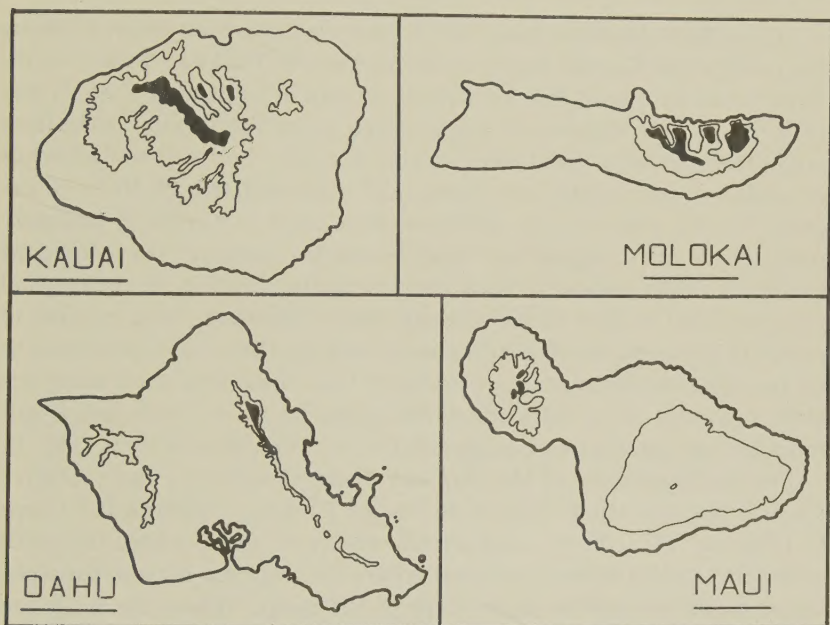


FIG. 2. Maps of islands showing summit swamp areas (solid black). On Kauai and East Molokai the areas shown are identical with the geomorphic provinces mapped elsewhere by one of the authors. On West Maui the areas shown approximate those mapped by Foster as peat-forming (Soil type VI). The area shown on Oahu is that roughly marked out by topographic conditions and known clay occurrence. These areas indicate according to present knowledge the probable limits of occurrence of ceramic clay, usable deposits being restricted to small pockets within the swamp region. On the basis of plant and bog conditions, some botanists feel that the area of clay occurrence may be somewhat larger on the higher area of West Maui, and smaller on the low summit swamp of Molokai, than shown here (St. John, personal communication).

the aggregate some three or four tons of clay have been packed out of the mountains and brought into Honolulu. Its ceramic and petrographic properties will be described in a later section.

During the summer of 1938, a one-day visit was made to clay localities on West Maui, a half day was spent in the area of clay occurrence on East Molokai and two days were spent in the Kokee area on Kauai, largely in examination of potential clay localities. Samples were col-

lected and trials made which permit some general discussion of the clays and localities on these islands, though we have far less practical knowledge of these than of their counterpart on Oahu.

DESCRIPTION OF LOCALITIES

OAHU

All the Oahu localities from which good clay has been taken lie along the crest of the Koolau Range from the head of Waikane Valley northward to the vicinity of Puu Kainapuaa, a peak in Latitude $21^{\circ}36'$ North (Fig. 2). In this distance of about seven miles the summit elevations range from 2,100 to 2,900 feet. On the east side the steep-walled heads of valleys form a nearly continuous cliff with declivity of 50 to 70 degrees. On the west, though the range slope for 4 or 5 miles is maturely dissected to very rugged and heavily-wooded country, the accordant interfluvial ridges appear to stand in close approximation to the original constructional surface of the volcanic dome. Moreover, in a number of places in this area, small patches are shown by the topographic map to be but slightly dissected. It is probable that these few small areas are truly remnants of an old surface, which has for a very long period suffered neither degradation nor aggradation to a significant extent (Fig. 3).

The chief exposures of the clay have been revealed by the extensive trail-cutting operations carried on by the Civilian Conservation Corps in 1934 and 1935. They occur almost wholly in places where the trails cross fairly gentle slopes, and never where the trails are cut against steep banks below the gentler upper slope of the range. Where the trails are on the constructional surface, on the lee side of the crest, the clay bed is commonly found in the trail itself, or in a low bank on one side. On the other hand, on the windward or eastern side, where the mountain slope is a cut surface, no clay is found except in the few places immediately at the crest where the clay bed is exposed in section.

The plant cover in the Oahu localities consists of open swampy scrub, with conspicuous club mosses and ferns. In the more protected spots and along the slight depressions at the head of drainage are remnants of a forest, dominated by the ohia lehua (*Metrosideros*). The general aspect is that of a cover which was formerly more largely forest, broken by the open grassy areas which represent tension zones, where the forest has not maintained itself against the destructive effect of wild hogs and of man. In the strict botanical sense there is no plant complex which could be called a bog, comparable to that on the other islands.⁴

⁴ This view has been expressed informally by Dr. H. St. John, Dr. Constance Hartt, Miss Marie Neal and Miss Lucy Cranwell, all botanists familiar with upland forest conditions in Hawaii.

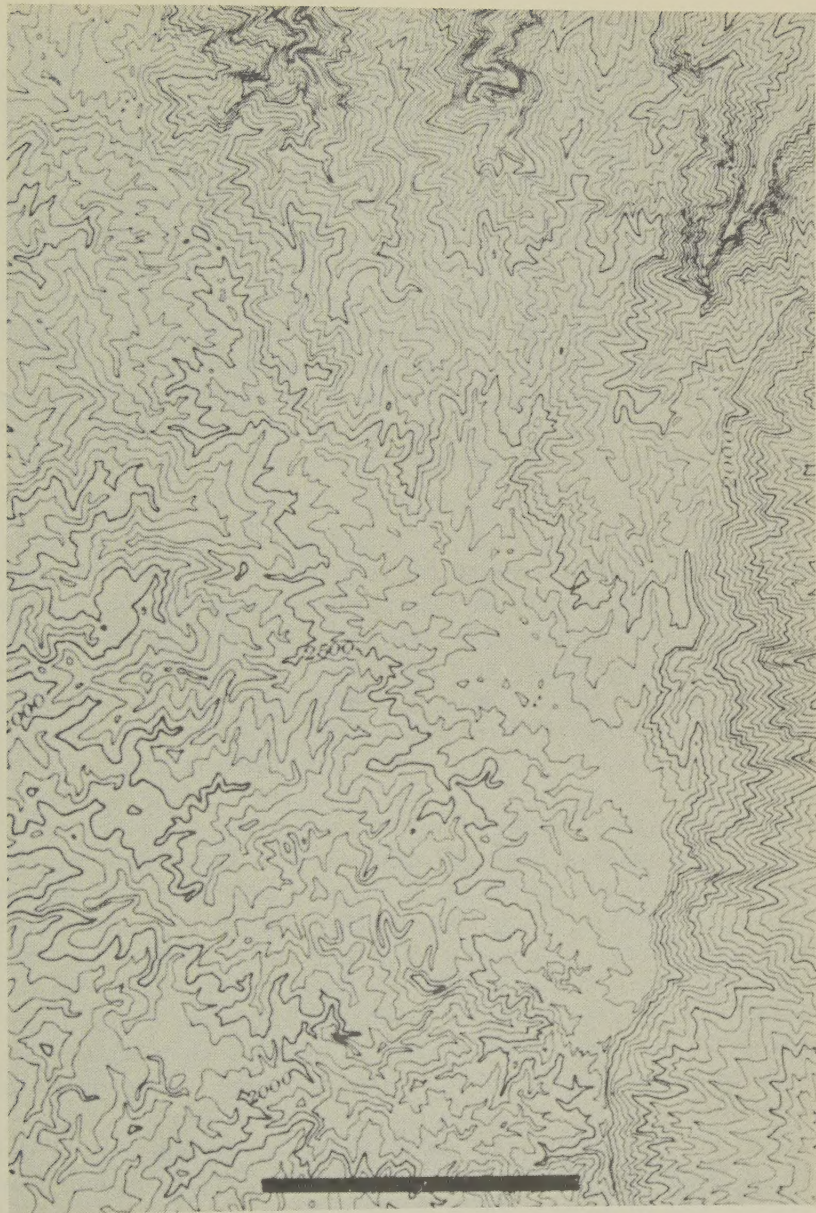


FIG. 3. Contour pattern of the summit of the Koolau Range at the northern end of the area of clay occurrence on Oahu, showing comparatively smooth, little-dissected, probable remnant of constructional surface. To the east is the steep, nearly continuous cliff formed by the heads of windward valleys. The heavy line is one mile long. Contour interval 100 feet. Photograph from the blue-and-brown U.S.G.S. sheet.

The largest deposits which have been found, though not prospected in detail, probably cover one or two acres and the total area is not known to exceed five acres. The typical stratigraphic section shows at the top a 6 to 9-inch mat of peaty material, in places almost wholly plant debris, of dark brown to black color. Below this layer and quite sharply marked off from it by its color and the scarcity of plant roots is the light gray clay. Commonly the clay is but one or two inches thick; locally, for a few feet it may reach 6 to 8 inches in thickness. Below, the clay grades in an inch or two to less pure clay, usually brown, buff or red in color and often lumpy or stony, showing original igneous rock structures. In this layer there may appear more roots than in the clay layer above. Such root stems as pass through the gray clay evidently do not branch effectively into the pure gray clay layer (Fig. 7).

MOLOKAI

East Molokai, West Maui and Kauai have in common the fact that they are high volcanic domes which have been deeply dissected on one or more sides and display near their summits conspicuous tabular areas of sloping bog which represent remnants of original constructional surfaces. These surfaces have been reduced but little by weathering and slope wash. Moreover, on each of these islands, though in differing degree, the vegetation of these upland swamps is of distinctive bog type.

The Summit Swamp province⁵ of East Molokai stretches for about 8 miles northwestward from Kamakou summit at 4,970 feet, past the steep-walled heads of Pelekunu and Waikolu valleys and with a branch between these valleys, to the elevation of about 2,500 feet at a point overlooking the Leper Settlement of Kalaupapa. Only the portion from Waikolu eastward is notably swampy. There are two other distinct sections of the Summit Swamp, one lying between elevations of 3,600 and 2,300 feet, east of Wailau Valley, and the other on the spur between Wailau and Pelekunu Valleys at 3,300 to 4,600 feet and entirely surrounded by the merged heads of these profound valleys. The total area of swamp mapped on the U.S.G.S. topographic sheet approximates six square miles (Fig. 4).

Clay was collected by one of us (C. K. W.) at two points on the trail west of the locality Pepeopae at the southwest rim of Pelekunu Valley, and was seen at various points in the vicinity. From present scanty knowledge of this little-visited country it may be presumed that clay occurs rather generally through the summit swamp area, and that, sporadically, patches of six inches to a foot or more thick may be found.⁶

⁵ This name is applied to this area as one of the geomorphic divisions of Molokai. (Wentworth, C. K., *First Progress Report, Territorial Planning Board*, Plate 8, 1939.)

⁶ Presence of clay in this area had been noted by Mr. and Mrs. George P. Cooke, who pointed out localities and assisted in other material ways.



FIG. 4. Contour map of portion of the summit swamp of East Molokai, showing Waikolu Valley on the west side and part of Pelekunu Valley on the east. The heads of leeward, south-facing valleys are also shown; in the middle is the sloping remnant of the original dome surface in which clay occurs. The heavy line is one mile long. Contour interval 50 feet. Photograph from the blue-and-brown U.S.G.S. sheet.

Clay seen here was in general a little darker gray than that most seen on Oahu, though at one point a notably clean, very light cream to gray clay called "Molokai select" was found. The thickest clay beds seen were 12" to 18" thick and were found beneath a mat of 1 to 3 feet of fairly clean peat. Beneath the clay layer in many places was a marked limonitic layer two or three inches thick, with buff or grayish weathered rock beneath. The parts of the summit swamp traversed are marked by open areas of grass, sedges and diminutive ohias dwarfed from their usual tree-like habit, surrounded by larger trees and ferns at the margins of the flatter areas, where better drainage occurs. The vegetation is more shrubby and less a prostrate mat than on the bog areas of West Maui.

MAUI

A one-day visit was made to the West Maui summit peak, Puu Kukui, elevation 5,788 feet, in company with Dr. H. A. Powers of the



FIG. 5. Detail of surface of West Maui bog at about 5,250 feet. Area shown is about 2 feet across. Very few plants are more than 6 inches high. Among the plants is the small tuft-like sedge, *Oreobolus fursatus*, the rosette-formed lobelia sp. and the diminutive ohia (*Metrosideros*), with oval leaves.

U. S. National Park Service. The chief summit swamp area of West Maui is the circular, filled bowl of Eke Crater, with several smaller areas lying down slope to the northeast and with two areas near the summit of Puu Kukui. The entire area mapped as swamp scarcely exceeds a square mile and lies at elevations from 2,600 to 5,700 feet. Only

the small area lying north of the Puu Kukui summit was examined. Here, between 5,200 and 5,700 feet, there are several small areas covered with bog vegetation forming a striking, carpet-like surface and with but few plants rising over a foot from the ground (Fig. 5). As elsewhere the open bog areas are surrounded by a somewhat scrubby forest of taller bushes and trees at the margins of the tabular, ill-drained areas. Here the peat is a clean, compact mass of plant material of rufous color, found generally to be two to four feet thick. With considerable digging a few patches of rather dark clay, a few inches thick, were found, with a poorly marked layer showing limonitic accumulation below. It is quite possible that, in some parts of the summit swamp, thicker, lighter-colored clay, of presumptively better ceramic quality may be found; so far as limited observations to date indicate, the clay of West Maui is darker in color and less abundant than that of East Molokai, despite the more perfect development of bog vegetation.

KAUAI

On Kauai, as on other islands, known occurrences of clay passing ceramic tests are restricted to the summit swamp area. A sample of clay was collected at about 1,200 feet along the power transmission line which follows the ridge immediately east of Hanalei Valley, but this clay, like a number of other buff clays from moderate elevations on Oahu and elsewhere, has not proved satisfactory.⁷

The summit swamp of Kauai slopes for about 12 miles northwest from the highest point of the island (Waialeale, 5,080 and Kawaikini, 5,177) to a point at about 4,000 feet overlooking the precipitous northwest "napali" (the cliffs) coast of Kauai. Two small isolated remnants of the summit swamp (Alakai Swamp geomorphic province) mark the crests of interfluvial ridges in the area to the north which is dissected by the three great rivers Hanalei, Niihama and Wainiha of northern Kauai (see Fig. 2). The total area of the summit swamp province probably does not exceed 15 square miles.

Two days were devoted to a reconnaissance in the western end of the Alakai Swamp area, where several samples of clay were collected.⁸ In so brief a time, it was only possible to traverse perhaps 8 or 10 miles of

⁷ This locality was visited in company with Joel B. Cox, Engineer of McBride Plantation, and keenly interested in the geologic problems of Kauai, who conducted the author (C.K.W.) to many other points of interest.

⁸ A part of the first day was spent in the company of Zera C. Foster, U. S. Bureau of Chemistry and Soils, who was engaged in completing a soil survey of the territory and who has made valuable contributions to understanding of soil-forming processes in Hawaii. The pit from which the largest and best-quality clay samples were collected was first opened by A. J. MacDonald, territorial forest ranger stationed at Kokee, who directed the writer (C.K.W.) to it.

trail, always returning by the same route, and to take clay from a few pits dug for the purpose. The Alakai Swamp as a whole is very little known, and but few persons have traversed any considerable part of it, and then only by definitely restricted routes.

The swamp is a sloping, upland bog, similar to those of Molokai and West Maui, whose open areas of grass and shrubs are surrounded by trees and more continuous forest around the margins and at the heads of invading drainage ways (Fig. 6). The features of the swamp, both its



FIG. 6. Surface of bog in Alakai Swamp above Kokee, showing characteristic margin of the forest. Most of the plants in this area are 1 to 2 feet high with a few shrubs reaching 3 or 4 feet in height. They include grasses, shrubby ohias and the rare sundew, *Diosera longifolia*.

bog vegetation and its soil profile of peat, clay and limonitic sub-soil layer, are the results of the extremely imperfect soil drainage coupled with very high rainfall.

The Alakai area shows broader areas of bog than were seen on the part of East Molokai visited. In the Alakai area the clay was found underlying 6 inches to more than 2 feet of clean peat. In some sections, only 3 to 6 inches of rather dark clay, with numerous plant roots, was found. However, at the pit opened by A. J. MacDonald, the following section was measured. This pit is located in the fifth bog clearing and about 40 minutes walk beyond the crossing over a branch of Kawaiko Stream at B.M. 3698 and in the vicinity of spot elevation 4,024 ft.

Top	Grassy surface of bog	
	Clean peat, with little mineral debris	24"
	Dark gray clay, soft, with numerous plant roots	6"
	Light gray to cream-colored clay, with hard, secondary masses (lithomarge) in upper part	Averages 15"
	Grades downward to stonier layers of buff color	
Base concealed		

This pit is in the midst of a rather uniform area of bog and the thickness of the clay suggests that workable thicknesses might be found beneath perhaps two feet of peat under one or two acres or more.

HAWAII

Small areas near the summit of the Kohala dome of Hawaii have been mapped by the Federal Soil Survey as peat-bearing areas in the same category as Alakai Swamp of Kauai. Clay has been reported as lacking, or of poor quality;⁹ the area has not as yet been visited by us.

SUMMARY OF OCCURRENCE

Certain generalizations seem justified by the preceding observations. Restriction to summit swamp areas is complete, if the Oahu locality can be regarded as such. The small size of the area and its lack of a markedly tabular aspect is opposed to such a classification. On the other hand, the topographic map, particularly the blue and brown printing, from which the culture and printed names are omitted, shows clearly a much less dissected and generally smooth topography at the summit of the range in the area where clay has been found, and the general conditions of drainage are very similar to those of the margins of several of the true bog areas (Fig. 3). From the standpoint of soil formation, this Oahu area may probably be regarded as marginal to the more typical and larger summit swamp areas of Kauai, Maui and Molokai.

The essential feature of the summit swamps is retarded drainage, enhanced by high rainfall. Rainfall in the Alakai Swamp of Kauai ranges from 450 down to 150 inches, the latter value being found near the west end where samples of clay were collected. Rainfall in the Puu Kukui area of West Maui is about 350 inches to somewhat over 150 inches. In the clay-yielding area of Oahu annual rainfall ranges from 250 to 300 inches. Apparently soil conditions suitable for clay formation may develop with a large range of annual rainfall, though all the areas receive high rainfall, and swampy conditions are general.

In all areas except that of Oahu, plant formations are of true bog character. These localities were studied during the summer of 1938 by a party

⁹ Cranwell, Lucy, Personal communication.

of bog specialists headed by Dr. Carl Skottsberg. The results of their special studies have not yet been compiled or published. However, the distinctive nature of the plant cover of the bog areas is very apparent, even to a casual observer. Development of this special floral assemblage, with the stunting of certain plants which normally grow to larger size, and the accumulation of the peat is the result of a combination of causes and effects which include poor soil drainage, high soil acidity and reducing conditions which have led to the development of a relatively iron-free clay from a rock originally rather high in iron and comparatively low in silica.

With a few local variations there are three characteristic layers in the soil profile from the top downward, the peat or humus dark soil at the top, an intermediate layer of clay of varying quality and freedom from plant roots and at the bottom a more or less definite layer indicating accumulation of iron. Below this is weathered rock of various colors (Fig. 7). The soil conditions are succinctly epitomized by Foster as follows:

"VI ALAKAI-KAWELA-PUU KUKUI ASSOCIATION

Occupying gently rolling more or less flat-topped areas in high rainfall belt, best developed between altitudes of 4,000-5,000 feet but occurring at lower elevations of 2,500 feet in places, there are areas wet enough and cool enough to favor the accumulation of peat. Open areas of grasses, sedges and shrub ohia surrounded by taller ohia and ferns form a characteristic vegetation on poorly drained areas. Larger ohia and associated vegetation borders drainageways. The soils are in part peat and muck and in part gray mineral soils, with a shallow limonitic transition zone to gray soft rock. These areas have an economic value in their ability to absorb water and retard quick run-off."¹⁰

PRODUCTION METHODS

Except in the few places where the clay has been exposed in trails, prospecting consists of sinking a small spade into the turf mat of the perennially water-soaked surface of open, non-forested areas to determine the thickness of the light-colored clay layer. On Oahu only two or three places have been found where a thickness of 8 inches is maintained over an area as much as ten feet square. Under such conditions digging the clay is a laborious operation, involving the stripping of the humus layer from the top and hampered by rain, water-soaked ground and the extreme toughness of the clay.

The first few hundred pounds of clay dug were carried out by C.C.C. workers, camped in the mountains for trail work and willing to pack it out at a stipulated rate per pound, on their week-end holiday trips to

¹⁰ Foster, Zera C., Soils of Hawaii: *Territorial Planning Board, First Progress Report*, 63, 1939.



FIG. 7. Exposure of Koolau clay at Kawailoa-Summit Trail junction. The dark area near the top is a mat of low-grade peat. Below it is the light gray clay with a few plant roots and carbonaceous remnants in it, and near the bottom the clay grades into a stonier, more ferruginous layer. Thickness of whole section about 30 inches.

town. Several efforts were made to use horses or mules as pack animals, but extremely muddy trail conditions, increasing damage to trails from landslides and occasional loss of animals off trails made this an unsatisfactory method. Late in 1937, nearly two tons of clay was packed out to the Forest Reserve boundary by four Filipino laborers on a contract rate and was further transported by pack horses to the paved highway.

From the deposit one can collect by hand nearly pure balls of clay which might go directly into a ceramic article, but in process of digging by shovel a considerable quantity of twigs and lumpy material is incorporated. In preparing the clay for use, the lumps from the pit are crushed after drying and put to slack in barrels of water. Some impurities settle out and twigs, leaves and the like are in part floated off. The slip is strained and used directly in mold work or further dried out in plaster boxes for wheel and coil work.

CERAMIC PROPERTIES

GENERAL APPEARANCE

In the discussion that follows, the Oahu or Koolau clay, which alone has been used and tested in substantial amounts, must be regarded as the type Hawaiian ceramic clay, as compared with the Molokai, Maui and Kauai clays, respectively. It should be recognized, that all these clays are variable, and that each type in any particular discussion is in reality the particular sample of a few pounds or production lot of one or two tons; subsequent lots, while similar, may be appreciably different in appearance and ceramic behavior.

The Koolau clay when dry is light gray in color (pale to light olive gray, (23'''' e)).¹¹ In the outcrop, when wet, the commonest color is a light to medium neutral gray; in a few places it is lighter gray or almost white. The damp clay is extremely tenacious and tough; when slightly more water is worked in, it becomes a highly plastic mass. To the feel and when tested between the teeth it is very fine grained and almost entirely free of grit.

The common Molokai clay is slightly darker and less pearly gray than the Koolau clay; a less common variant called "Molokai select" is a light cream color. The sample of Maui clay collected is much darker gray than most of the Koolau clay discovered and used. Some of the samples of common Kauai clay are darker, somewhat buff, and less neutral gray than the Koolau; the lower layer in the MacDonald pit is a light, pearly gray clay as fine-textured as any of the Koolau clay. This clay, in particular, when it sets from slip on plaster takes on an extraor-

¹¹ Color terms and symbols are those of Robert Ridgway, *Color Standards and Color Nomenclature*, Washington, 1912.

dinarily smooth, satiny appearance which approaches a polish. All the varieties of Hawaiian clay can be given a semi-polish by burnishing when dry and pieces so finished fire in the kiln to an extremely attractive saddle-leather aspect.

The California clay used by the Hawaiian Potters' Guild is produced by the Bauer Pottery Company and is understood to be a blended clay containing fractions from the Ione formation and from other Eocene formations.^{12,13} This clay is tan in color (21'''f) and is much more gritty. It is less tenacious and hence more satisfactory for work on the potter's wheel. On the other hand, the Koolau clay in the form of slip is distinctly superior to either the Ione clay or the Monmouth clay in the making of molded pieces. This is because, from slip of the same consistency, a piece becomes set and dried sufficiently to clear the mold very much more quickly with Koolau slip than with either of the others used.

A commercial variety known as Monmouth clay is also used in Honolulu and this is reported to be produced in the Colchester district of Illinois. Both this clay and its counterpart formerly produced at Monmouth, Illinois, are from the Cheltenham group of Pennsylvanian clays.¹⁴

In most respects the Monmouth clay is intermediate in properties between the Ione and the Koolau clay. It is slightly darker in color than the Koolau clay, nearer a smoke gray (21'''f). Other properties are indicated in the tests reported below.

MECHANICAL COMPOSITION

Methods of determining particle-size distribution in clays are numerous and far from standardized. There is no occasion in this paper to add to deflocculation procedures or forms of subsidence apparatus. The most practical approach suggested a hydraulic classification of particles in the electrolytic condition obtaining in the practical operations of the pottery workshop. Therefore the tests have been carried out with tap water from the artesian system of Honolulu. This water, in parts per million at Beretania station contains the following: calcium, 6.7; magnesium, 6.4; sodium, 36; potassium, 1.6; chloride (Cl), 40; sulphate (SO_4), 6; bicarbonate (HCO_3), 76.¹⁵

The general distribution of particle sizes was determined for the Koolau, Ione and Monmouth clays by the plummet method,¹⁶ in which the

¹² Sutherland, J. Clark, Letter dated February 26, 1938, addressed to Dr. J. P. Buwalda.

¹³ Allen, V. T., The Ione formation of California: *Univ. of California, Bull. Dept. Geol. Sci.*, **18**, No. 14, 347-448 (1929).

¹⁴ Leighton, M. M., Chief, Illinois Geological Survey, Letter dated April 21, 1938.

¹⁵ Bryson, L. T., *Board of Water Supply, 7th Biennial Report*, **41**, 1939.

¹⁶ Schurecht, H. G., *Jour. Am. Ceramic Soc.*, **4**, 816 (1921).

decreasing density of a clay suspension is measured by weighing a cylindrical plummet in the upper half of the suspension. The buoyant effect of the suspension on the plummet at a given time is exactly complementary to the weight retained at the same time on a pan at the bottom of the same column in the Odén subsidence method. The weight of the suspension was determined by a pycnometer, the mixture was then placed in a jar and shaken, and weighings of the plummet taken. The method has the superiority that the end points, both of the full suspension and the clear water, are known, and plotting and interpretation are thus better controlled. Moreover, weighing the plummet in several

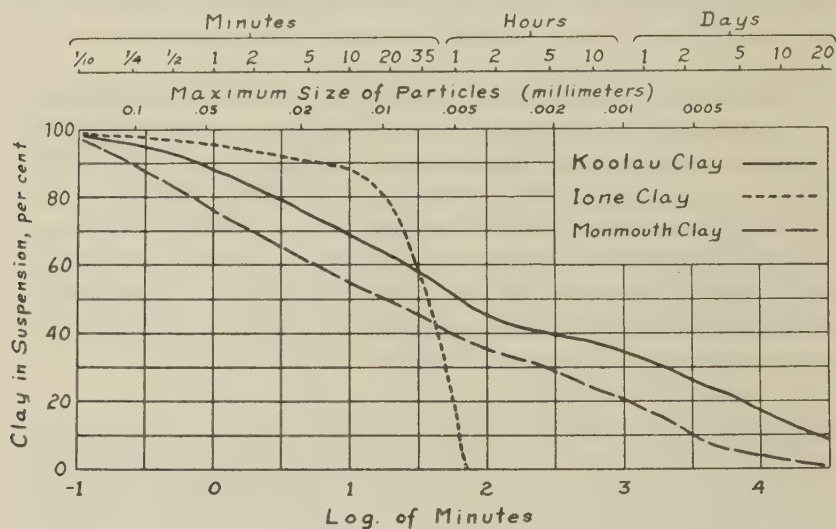


FIG. 8. Graph showing rates of subsidence of Koolau, Ione and Monmouth clays, as used in ceramic workshop at Honolulu. Determinations by the Schurecht plummet method, as described in the text.

samples, in a balance not continuously at the disposal of the operator, is more practical than when working with an Odén setup. Each set of weighings included a weighing of the plummet in a control jar of clear water which furnished a control correction for slight changes of temperature in the laboratory. The mechanical composition was derived from the subsidence curve by the tangent-intercept method.¹⁷

The results are shown in Fig. 8. The Ione clay was notable in the rapidity with which the settling was completed, the subsidence being nearly complete in about 1 hour. The amount of material settling slower than 1 mm. per minute, and thus under about .005 mm. in size is negligible

¹⁷ Calbeck, J. H., and Harner, H. R., *Industrial and Eng. Chem.*, **19**, 58 (1927).

in the Ione clay. On the other hand, about 31 per cent of the Koolau clay remained in suspension after one day, and 10 per cent after 11 days. In this respect, the Monmouth clay is intermediate, as shown in Fig. 8.¹⁸

SPECIFIC GRAVITY

Specific gravities of plastic clay, air-dried clay, fired biscuit and of the clay substance were determined. That of the latter was determined by a pycnometer; the remaining determinations were made by weighing the clay in air and immersed in mercury by means of a saddle and stirrup arrangement. The resulting values are tabulated below.

TABLE OF SPECIFIC GRAVITIES OF CLAYS IN DIFFERENT CONDITIONS¹

Condition	Koolau Clay	Ione Clay	Monmouth Clay
Clay substance (By pycnometer)	2.65	2.53	2.56
Plastic clay wedged for use	1.87	1.81	1.92
Air-dried clay	1.67	1.78	1.88
Fired biscuit	1.62	1.62	1.75

¹ All values are averages of from 2 to 8 determinations.

POROSITY

Simple saturation tests of porosity were made of the several fired test pieces by boiling in water. Results of these tests and porosities computed by several methods are given in the following table:

TABLE OF PERCENTAGES OF POROSITY¹

	Koolau	Ione	Monmouth
Total porosity of wet clay, by computation from grain specific gravity	47.6	45.5	41.1
Total porosity of wet clay, by computation from water loss	48.0	43.0	40.3
Total porosity of dry clay by computation from grain specific gravity	36.9	29.4	26.7
Open porosity of fired biscuit	35.13	33.75	26.16

¹ Averages from determinations on three samples.

PLASTIC TENSILE STRENGTH

Comparative measurements on the three clays were made by determining the lengths extruded from a die before self-rupturing took place.

¹⁸ The Ione clay and possibly the Monmouth clay are not simple, raw clays but have undergone some blending and grinding.

For all the tests herein described, standard pieces were made by forcing the wedged clay through a square die attached to a large-size, hand-driven food chopper. This device, using a round die, is used for producing clay coil material in quantity for making large coiled pottery pieces. In making the tests, the die was faced downward from a point of sufficient height and the clay forced out slowly and as uniformly as possible, until the extended clay broke from its own weight. As shown in the following table the Koolau has a much higher plastic strength than the Ione clay, and the Monmouth clay shows intermediate strength.

TABLE OF PLASTIC TENSILE STRENGTH¹

Clay	Length at Rupture (Inches)			Average Breaking Strength	
	Trial 1	Trial 2	Trial 3	Grams per sq. cm.	Pounds per sq. inch
Koolau	63	78	72	332	4.72
Ione	46	43	40	195	2.76
Monmouth	57	55	57	270	3.83

¹ The clay was tempered and wedged to the consistency commonly used; there was no rigorous control to insure optimum strength.

LIQUIDITY AND DENSITY OF SLIP

In preparation for mold clearance tests, slips were mixed from each of the three clays to a standard consistency approximating that used in mold work. This consistency was measured by timing the draining of a funnel through a cylindrical opening drilled in a metal piece at the bottom. The slips prepared drained from the funnel in 50 seconds, as compared to 35 seconds for water. The densities were: Koolau clay, 1.410; Ione clay, 1.245; Monmouth clay, 1.359. The far higher density of the Koolau slip having the same liquidity as a Ione slip is striking, though the explanation is somewhat complex. In fact, such a slip, because of its greater density, passes through the funnel with such rapidity as to appear less viscous than it really is. In reality, the viscosities of any of several slips having a standard rate of draining from the funnel are directly proportional to their densities. In practice this means that slips mixed so as to appear of equal liquidity in pouring, or in passage through the funnel, the Koolau slip contains nearly 70 per cent more clay substance per unit of liquid measure. Presumably this is in part the explanation of the more rapid settling and greater firmness of molded pieces made from Koolau than from Ione clay. As in other respects the Monmouth clay occupies an intermediate position.

MOISTURE LOSS AND SHRINKAGE

Standard test pieces, 1" by 1" by 2½", were made by cutting square extrusion pieces to a standard length in a simple jig. The following table shows the progressive loss of moisture and the shrinkage on drying and firing.

TABLE OF VOLUME AND MOISTURE CHANGES¹

	Koolau			Ione			Monmouth		
	Volume (cc.)	Per cent loss ²		Volume (cc.)	Per cent loss ²		Volume (cc.)	Per cent loss ²	
		Volume	H ₂ O ³		Volume	H ₂ O ³		Volume	H ₂ O ³
Plastic condition	41.90	—	—	41.12	—	—	41.50	—	—
Air dried	34.80	20.4	34.6	31.75	29.5	31.6	33.00	25.8	25.8
Fired	32.30	7.2	9.4	30.70	3.3	12.0	31.95	3.2	10.7

¹ Values are averages from three or more determinations.

² Percentages referred to air dry volume and weight as base.

³ Moisture loss is per cent by weight of water lost to total air dry weight of test piece.

SLACKING TEST

Marked differences in slacking behavior were noted, partly direct and partly caused by differences in structure set up in passing through the extrusion die. The Koolau clay placed under water with the linear axis of extrusion vertical, showed immediate opening of tangential cracks all around the square margin of the transverse exposed face and sloughing off of thin laminae progressively all around the vertical sides of the column. The mass typically reduced to a pile of soft, thin flakes. The Ione clay slacked most rapidly with a spalling off of larger flakes from edges, without displaying marked relationship to the axis of extrusion. Later the whole block was split parallel to this axis into three or four columns which toppled over. The Monmouth clay yielded very slowly to slacking action and in all early stages showed a compact, unpenetrated core.

MOLD CLEARANCE

Practical consequences of several of the physical peculiarities shown by the above tests are found in the exceptional adaptability of the natural Koolau clay to the process of pouring and setting in plaster molds. It has been consistently found that pieces cast from Koolau slip become sufficiently dry to clear the mold, and sufficiently tough to be handled, in one-fourth to one-sixth the time required by pieces cast from the

Ione clay. With a thoroughly dry mold, small, compact articles of Koolau clay will often clear the mold within less than an hour after commencing the pouring, and even with larger shapes, several pieces can often be taken from a single mold in a single day, a feat quite impossible with the Ione clay. In this respect the Monmouth clay is again intermediate.

It is notable, also, that the Koolau clay when blended with other clays greatly improves their setting up and mold-clearing qualities. In general, so small a proportion as $1/5$ to $1/10$ of the Koolau clay with Ione or similar clays will reduce to one-third or less the time required for clearing of molds. We have no rigorous physical or chemical explanation of this striking property of Koolau clay, but it appears to be related to (a) the density of the clay substance, (b) the large amount of material in the colloidal state and (c) the large amount of clay substance per unit of volume of slip of a given appearance of liquidity (hence smaller amount of water necessary to be removed to leave a specified amount of residue).

FUSIBILITY

The Koolau clay has a somewhat lower fusion point than the Ione clay, as well as a shorter firing range. Best results are obtained by firing the Koolau clay to cone 07, which at the heating rate used is probably about 980° C. Care has to be taken not to place articles made of Koolau clay in parts of the kiln where temperatures more than one cone higher are reached, equivalent to about 1010° C., whereas articles made of Ione clay can safely go to considerably higher temperatures. The lower fusion point of the Koolau clay is probably caused by its high content of titania.¹⁹

PROPERTIES OF MOLOKAI, MAUI AND KAUAI CLAYS

Generically, the clays from other islands are found to be similar to the Koolau clay of Oahu in their behavior in casting and drying. However, some differences are noted, greater than those between production lots of the Koolau clay used to date. The Molokai clay as collected is most similar to the Koolau clay; probably the "Molokai select" is equal to the best Koolau and the "Molokai common," or gray Molokai clay, is somewhat darker in color and forms a somewhat less firm body. The Maui clay is a much darker gray and appears more susceptible to cracking as it dries. It is probable that a careful search would reveal better grades than were found during the brief visit made. The Kauai clay collected from several points along the Alakai Swamp trail was gray to slightly buff in color and of poorer quality than the standard Koolau

¹⁹ Ries, H., *Clays; Occurrence, Properties and Uses*, New York, 144-148 (1927).

clay. That from the MacDonald pit, however, is light pearly gray and is exceptionally fine grained. Indeed it appears to be so rich in colloidal clay substance that it has a detrimentally high shrinkage and also offers difficulty in casting. Whereas thin castings made of this clay set very rapidly to an extremely tough condition, with a fine, satiny surface and clear the mold quickly, it is somewhat difficult to get thicker pieces from this slip owing to the tendency for the piece to start shrinking and separation from the mold while the mold is still filled with slip. It is quite likely that less extreme types of this clay will be found in the Alakai Swamp area, and also that such clay can be successfully blended with other types less rich in colloidal material.

COMPOSITION OF THE CLAY

CHEMICAL ANALYSIS

The clays as received for analysis in Washington were well sealed in glass jars and still very moist, 40, 14, 34 and 35 per cent, respectively, of water above the air-dried weight. They were dried in air of about 40 per cent humidity for analysis. A few minor constituents were determined in some of them but, as these did not seem significant, the main attention was given to the major constituents, of which titanium was conspicuous. This was separated from aluminum by means of cupferron, after removing iron as sulphide in a tartrate solution. A colorimetric check showed the titanium to be of the order found gravimetrically. Organic matter was determined by dissolving the silica and most of the alumina in a mixture of hydrofluoric and hydrochloric acids, filtering off the crude organic matter and determining it by means of concentrated hydrogen peroxide. The loss on ignition was then corrected for H_2O —and for organic matter. The other constituents were determined by usual methods.

All the iron is reported as Fe_2O_3 . Ferrous iron could not be determined accurately on account of the presence of organic matter. The apparent figures for FeO were 1.47, 1.47, 3.57 and 0.77 per cent, respectively, in the four clays but these figures are not entitled to much weight. It seems clear, however, that most of the iron in clays 1, 2 and 7 is in the ferric condition.

Comparison of the analyses of the three clay samples shows a marked variation in some oxides. Samples 1 and 2 were field duplicates and are similar though by no means identical. Sample 7 was a notably white clay from a point where the marshy conditions might be a little more extreme. The SiO_2 is more than 20 per cent higher, and the TiO_2 about 10 per cent less than in samples 1 and 2; alumina and iron oxide are

TABLE NO. 1
ANALYSES OF HAWAIIAN CLAYS, BASALT AND SOIL

	1	2	5	7	A	B
SiO ₂	33.88	39.72	23.24	57.00	49.88	42.13*
Al ₂ O ₃	25.69	25.12	9.16	21.93	13.79	10.41
Fe ₂ O ₃	8.61	7.38	3.97	3.23	12.26	25.12
MgO	0.92	0.61	0.44	0.86	6.12	0.39
CaO	0.06	0.05	0.13	0.03	9.59	0.44
K ₂ O	2.76	3.01	1.23	4.18	0.17	0.60
Na ₂ O	0.25	0.21	0.11	0.40	3.30	0.19
Li ₂ O	0.04	—	—	0.03	—	—
H ₂ O—	2.08	1.40	7.25	1.84	—	3.80
H ₂ O+	8.20	8.70	17.34	6.27	—	
TiO ₂	15.28	14.06	3.88	4.33	3.97	3.40
P ₂ O ₅	0.06	—	—	—	0.26	0.12
ZrO ₂	0.04	—	—	0.02	—	—
BaO	—	—	—	0.04	—	—
CO ₂ , MnO, SO ₃ , Cl, } N, Rare Earths }	None	None	None	None	0.67	0.58†
Organic matter	0.91	0.66	32.29	0.43	—	13.20‡
Total	98.78	100.92	99.30	100.61	100.26	100.38

1. Clay from crest of Koolau Range, at junction of Kawailoa and Summit Trails, Latitude 21°36', Oahu. (Acidity, pH=4.65; determined by L. T. Bryson.) Analysis by R. C. Wells.

2. Same locality as (1) above. (Acidity, pH=4.80; L.T.B.) Wells, analyst.

5. Peaty, humus layer above clay, same locality. (Acidity, pH=4.75; L.T.B.) Wells, analyst.

7. Lighter clay from head of small gully about 400 feet southwest of above locality. Wells, analyst.

A. Basalt, Koolau Mountains. Analysis by A. B. Lyons. (Cross, W., *U.S.G.S., Prof. Paper 88*, Analysis No. 19, p. 52, 1915).

B. Soil, red, Wahiawa district. (Kelley, W. P., McGeorge, Wm., and Thompson, Alice R., *The soils of the Hawaiian Islands: Hawaii Agricultural Expt. Station, Bull. No. 40*, Soil No. 5, p. 27, 1915.)

* Insoluble residue.

† Includes Nitrogen, 0.24; SO₃, 0.08; and manganese oxide, 0.26.

‡ Volatile matter.

about 4 and 5 per cent lower, respectively. There is no doubt that samples collected generally from different places in the clay districts of the several islands would show similar wide ranges of composition, while in general showing high enough silica plus alumina, and low enough iron, to possess ceramic utility.

The more normal gray clay is extraordinarily high in titanium; casual inspection of washed lag as well as mineralogical examination suggests

that much of the clay is high in ilmenite or leucoxene, and hence of comparable richness in titanium oxide, though the composition of the whiter sample 7 shows that a markedly smaller percentage of titania is found in some varieties. Although the clay is in general regarded as residual, washings of fine black rill silt, largely ilmenite, seen in the clay areas suggest that some local removal or concentration of ilmenite by mechanical transport may explain the variation in amounts of titania. Elements that might be associated with titanium, such as zirconium and rare earths, are absent. The percentage of titanium does not seem to run parallel with that of any other element, except possibly iron. They are high-titanium clays and seem to tend toward silica-alumina ratios higher than that of kaolinite.

MINERAL COMPOSITION

In thin sections the Koolau clay²⁰ appears to be a mixture of illite with small amounts of kaolinite, plagioclase and a black opaque mineral resembling magnetite or ilmenite. Certain areas of the clay minerals are brown in thin section and have higher refringence and birefringence than others. Measurements in oils on the fine colloidal fraction separated by sedimentation methods indicate that the refractive indices of different parts vary. Some have optical properties that suggest kaolinite, and others fall within the range recently reported for illite,²¹ in which the refractive indices increase with the ferric oxide. The highest value determined for gamma was 1.608 and for gamma minus alpha about .03. These values are close to those found by Grim for a sample of illite with 10.73% ferric oxide. An x-ray pattern of a sample of the Koolau clay was made through the courtesy of the State Geological Survey of Illinois. Dr. W. F. Bradley²² reports that this pattern indicates that the clay is composed of illite, some kaolinite and extremely fine quartz. The presence of quartz in the sample could not be established by optical examination. The chemical analyses of the Koolau clay (Table No. 1, Samples 1, 2 and 7) suggest that the potash, silica, alumina and part of the iron and water could be accounted for mainly by mixtures of illite and kaolinite. Grim, Bray and Bradley²³ consider that the composition of illite can be expressed by the formula $2K_2O \cdot 3MO \cdot 8R_2O_3 \cdot 24SiO_2 \cdot 12H_2O$, in which MO represents the divalent oxides of calcium and magnesium and ferrous oxide, and R_2O_3 the trivalent oxides alumina and ferric oxide.

²⁰ Samples 1 and 2, Table No. 1.

²¹ Grim, R. E., Bray, R. H., and Bradley, W. F., The mica in argillaceous sediments: *Am. Mineral.*, **22**, 813-829 (1937).

²² Written communication.

²³ *Loc. cit.*, p. 823.

The unusual feature of the chemical analyses of the Koolau clay is the presence of over 15 per cent of titania, which far exceeds the 8 or 9 per cent of titania previously reported in the soils of Oahu.²⁴ In more than 200 analyses of Hawaiian soils and sub-soils only about 10 per cent show more than 5% of titania, nearly all being in samples from the Hamakuapoko district of Maui. Nearly as many samples show less than one per cent, the median being 2.55 per cent.²⁵ The black opaque mineral in the clay was concentrated by elutriation and by the use of heavy solutions and gave a qualitative test for titanium. It is only weakly magnetic and is probably ilmenite. The black opaque mineral in Hawaiian lavas is usually termed magnetite, but Cross²⁶ found that the powder isolated with a magnet from a nephelite-melilite basalt on Oahu contained 13.4 per cent TiO_2 . A fair representation of the average content of the black mineral in the Koolau clay is indicated in the photomicrograph of Fig. 9. The amount present seems too small to explain the 15 per cent titania in the clay. The only other abundant titanium mineral in the heavy separation was leucoxene, the gray opaque alteration product of ilmenite. Two grains of anatase and one that possibly was rutile were observed among several hundred grains of ilmenite and leucoxene. W. F. Bradley of the State Geological Survey of Illinois compared the x -ray pattern of the Koolau clay with several titanium minerals and found the six strongest lines of anatase represented by weak lines suggesting the possible presence of some anatase.²⁷ He, however, did not compare it with the x -ray pattern of leucoxene. McCartney²⁸ found that small samples of leucoxene gave no x -ray pattern. Paul F. Kerr²⁹ reported that samples of leucoxene prepared by the writer (Allen) gave x -ray patterns too indistinct to recognize in a mixture of clay minerals. The composition of leucoxene is uncertain. According to Coil,³⁰ the leucoxene in the Permian sandstones of Oklahoma is an amorphous hydrous titanium oxide. Tyler and Marsden more recently have concluded that leucoxene is a microcrystalline form of rutile, anatase and perhaps brookite and recommend

²⁴ Lyons, A. B., Chemical composition of Hawaiian soils and the lavas from which they have been derived: *Am. Jour. Sci.*, **2**, 421, 29 (1896).

²⁵ Kelley, W. P., McGeorge, W., and Thompson, Alice R., The soils of the Hawaiian Islands: *Hawaii Agricultural Experiment Station, Bull.*, **40** (1915).

²⁶ Cross, Whitman, Lavas of Hawaii and their relations: *U.S.G.S. Prof. Paper* **88**, 22 (1915).

²⁷ Written communication.

²⁸ McCartney, G. C., A petrographic study of the Chester sandstone of Indiana: *Jour. Sed. Petrology*, **1**, 82-90 (1932).

²⁹ Kerr, Paul F., Written communication.

³⁰ Coil, Fay, Chemical composition of leucoxene in the Permian of Oklahoma: *Am. Mineral.*, **18**, 62-65 (1933).

retention of the name leucoxene for this material since it is not a mineral species.³¹ Because finely divided leucoxene mixed in a clay could escape detection by optical and x-ray methods which would reveal such minerals as rutile, titanite and anatase, it seems probable that the titania of

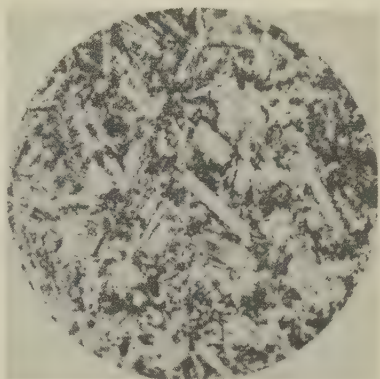
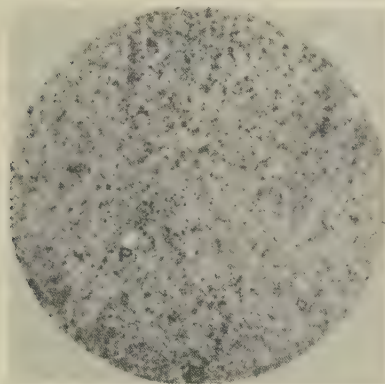


FIG. 9. (left). Koolau clay showing illite (I), kaolinite, ilmenite (solid black specks) and plagioclase (white rectangle above P). ($\times 54$)

FIG. 10. (right). Nodule showing ilmenite (solid black) and plagioclase altered to kaolinite. ($\times 31$)

the Koolau clay, which is not in the form of ilmenite, is present as leucoxene. A similar conclusion was reached by the writer (Allen) regarding the titanium in separations from Missouri diaspore clay which analyzed over 24 per cent titania³² and contained leucoxene but did not give the x-ray pattern of any titanium mineral.

PETROGRAPHY OF PARENT ROCKS

The occurrence in the summit areas of Mauna Kea and Kohala on Hawaii, West Maui and Haleakala on Maui, and perhaps elsewhere, of intermediate lava flows of trachytic or andesitic composition has been known in a general way for many years. This fact suggests the possibility that the clays of some of the summit deposits may not be wholly, or largely derived from such intermediate rocks, by weathering entailing less pronounced removal of iron and increase of silica and alumina.

Hard rock specimens are difficult to obtain in the near vicinity of the clay deposits and insufficient work has been done to give a comprehen-

³¹ Tyler, S. A., and Marsden, R. W., The nature of leucoxene: *Jour. Sed. Petrology*, **8**, No. 2, 55-58 (1938).

³² Allen, Victor T., Mineral composition and origin of Missouri flint and diaspore clays: *Missouri Geol. Survey, 58th Biennial Report*, App. **IV**, 11-13 (1935).

sive view of the succession of original lava flows. However, some specimens have been examined in thin section with the following results:³³

Four specimens collected at different points along the crest of the Koolau Range within the area of clay occurrence are olivine basalt, or olivine-basalt porphyry, with textures either typical of the fundamental Koolau basalt, or well within its range of textures. Olivine is abundant, also magnetite, and pyroxene. The feldspar is in the labradorite range. These specimens afford no evidence of late, summit lava flows on the Koolau Range of composition significantly less basic than the Koolau series generally.

No rock specimens were collected from the clay area on Molokai, nor on West Maui. Late capping lava flows of trachytic composition are known to occur on West Maui dome, but the specific relation of these to the clay deposits is unknown. As the West Maui clay seen in the field is uncommonly dark and appears to contain much dark mineral, thought to be ilmenite, it seems at least plausible that the clay may be derived in part from basalt.

In the vicinity of Kokee, Kauai, below the west end of Alakai Swamp, numerous road-cuts lead to the tentative field conclusion that both basaltic flows and intermediate flows occur on that part of the dome. Both are deeply weathered, but show rather contrasting features. The basalt is commonly dark red or purple in color, spheroidal in weathered structure, and shows clear vesicular texture. The supposed trachyte has less spheroidal structure, or none at all, is commonly light lavender to chalky white in color and not significantly vesicular. In places, slabby, light gray blocks of the "trachyte" lie imbedded in a buff, or tan-colored, slope-washed soil. Six specimens from this area were examined in thin section. Three of these are classified as olivine basalt or porphyry, showing moderate to much weathering. A fourth is described as "Clay, pseudomorphous after basalt or closely related rock. The preserved texture strongly suggests a common ophitic or intergranular Hawaiian basalt, rather than any marked differentiate. The secondary minerals are extremely fine grained and were identified tentatively as clay minerals."³⁴

Two specimens (H1935 and H1941) appear to be somewhat more acid than basalt. A certain parallelism of the feldspar laths was noted and the plagioclase is more abundant than in most basalts. Orthoclase was tentatively identified in one of the specimens. On the other hand, olivine, magnetite and pyroxene are present. In the Alakai area the clay may

³³ Winchell, Horace, Manuscript report based on microscopic examination of specimens collected by one of us, in comparison with extensive series of specimens of Koolau basalt of Oahu, and limited number of specimens from elsewhere in Hawaii.

³⁴ Winchell, Horace, *Op. cit.*

in part be derived from intermediate rocks, though basalts are present and appear to have constituted much of the parent material. It is concluded that the clay has been derived from basalt, perhaps exclusively so on the Koolau Range of Oahu, and to an important degree elsewhere. Despite the likelihood that much clay has also been derived from rocks of less basic composition, there seems no basis for concluding that such intermediate parent rocks are essential.

ORIGIN OF THE KOOLAU CLAY

Petrographic study of the Koolau clay suggests that the clay was derived from the weathering of basaltic lavas. It contains tiny grains of plagioclase altered to kaolinite at the edges but with the central cores of some grains sufficiently fresh that albite twinning can be distinguished between crossed nicols. Some of these were collected by washing large samples of clay, and their refractive indices indicated basic labradorite or acid bytownite.

Figure 10 shows a photomicrograph of a nodule of weathered rock collected from the same locality as the Koolau clay. The phenocrysts, probably originally plagioclase, are altered to clear white kaolinite, as shown by the interference colors of these areas which are first order gray (birefringence .005). Moreover, powders representing parts of them tested in oil have the refractive indices of kaolinite, and there is also a suggestion of the worm-like structure often assumed by kaolinite. The groundmass, which originally was probably composed of feldspar grains and ferromagnesian minerals, is now altered to a clay mineral having the properties of illite. The solid black is ilmenite or titaniferous magnetite. Titanium is present in the augite of some Hawaiian lavas and gives it a purple color in thin section. The ferromagnesian minerals of these nodules are too markedly altered to show their original nature. Thus, the relict plagioclase feldspars in the Koolau clay indicate that minerals of basaltic lava contributed to the formation of the clay, and altered nodules reveal that weathering in this area could furnish the clay minerals of which the Koolau clay is composed. Study of other specimens of rock in various stages of weathering, collected from the crest of the Koolau Range and the Alakai Swamp area, as reported above, also points to the same conclusion.

Further indication of the derivation of this clay from basaltic lava is afforded by the chemical analyses. Comparison with a representative analysis of basalt of the supposed parent rock (Analysis *A*), indicates that silica in the gray clays is decreased, while it has increased by nearly 10 per cent in the lighter clay. Alumina generally is considerably higher, as it remains while other oxides are removed. In the gray clays, titania

is present nearly four times the percentage found in the rock and iron is reduced by $\frac{1}{3}$ to $\frac{2}{3}$ of its original amount. There is great loss of lime, magnesia and soda, but marked increase in potash. That common changes incurred in lower level weathering are suggested by analysis *B*, though any series of analyses of soils will show much variation. However, in the soils, under laterization, iron oxides increase, commonly to twice the amount in the original rock, and alumina is slightly reduced in amount. Titania varies from much less than that in the rocks to somewhat more, in soils in which concentration appears to have taken place.

Since Deville's observation³⁵ of titania in bauxite, it has been regarded as a concentration of the insoluble material of the original rock. The titania apparently increases directly as the alumina is concentrated^{36,37} by weathering and decreases as the alumina is removed under other conditions.³⁸ In the 14 analyses of Hawaiian lavas given by Cross,³⁹ not including those of trachytes, the range for TiO_2 is from 1.48 to 4.05 per cent, with an average of 2.44 per cent. The average TiO_2 of 56 analyses of Hawaiian lavas listed by Washington is 2.84 per cent.⁴⁰ Maxwell⁴¹ reports that the average TiO_2 of ten lavas is 3.5 per cent and that it is the most insoluble constituent in Hawaiian soils, where its increase is proportional to the decrease in silica. A dark red soil with 31.45 per cent silica is stated to contain 7.62 per cent titanitic acid. McGeorge⁴² lists the chemical compositions of several lavas and the disintegration products derived from them. All show an increase in titania, alumina and iron and a decrease in silica during weathering of the lavas. From these observations the presence of titania in Hawaiian lavas and its concentration during weathering may be considered an established fact. But, to account for the 14 or 15 per cent of titania in the Koolau clay, either the parent rock was unusually high in titania or, what is thought more likely, there may have been some local placer concentration of the heavy mineral ilmenite.

Another feature of the weathering process that formed the Koolau

³⁵ Deville, H. Sainte-Claire, *Annales Chim. phys.*, 3rd series, **61**, 309 (1861).

³⁶ Coghill, William F., Titanium in bauxite ores and sludges: *Report of Investigation of U. S. Bureau of Mines*, No. **2867**, Rolla, Mo. (1928).

³⁷ Allen, Victor T., *Loc. cit.*, **1935**.

³⁸ Allen, Victor T., A study of Missouri glauconite, *Am. Mineral.*, **22**, 1181 (1937).

³⁹ *Loc. cit.*, 51 (1915).

⁴⁰ Washington, H. S., and Keyes, M. G., Petrology of the Hawaiian Islands, V. The Leeward Islands: *Am. Jour. Sci.*, **12**, 351 (1926).

⁴¹ Maxwell, Walter, Lavas and soils of the Hawaiian Islands: *Hawaiian Gazette Co.*, Honolulu, 80 (1898).

⁴² McGeorge, W. T., Composition of Hawaiian soil particles: *Hawaii Ag. Exper. St., Bull.* **42**, 6 (1917).

clay is the behavior of potash. In the papers of Maxwell⁴³ and McGeorge⁴⁴ a decrease in K_2O is shown in the soils over that present in the parent material. The samples of Koolau clay with over 14 per cent titania have about 3 per cent potash. The average of the 56 analyses of Hawaiian lavas by Washington⁴⁵ contains 1.02 per cent potash. Either the parent rock of the Koolau clay had a higher content of potash than the average of the Hawaiian lavas, or its being stored during the formation of illite prevented the usual loss that takes place during the formation of lateritic soil. Though trachytes⁴⁶ with over 5 per cent potash are known in the Hawaiian Islands, there does not appear to be good evidence that the clays have been formed from such less common rocks, especially since such trachytes have less than 1 per cent titania and this substitution would merely increase the difficulty of explaining the high titanium and the basic plagioclase in the Koolau clay. The conclusion appears justifiable that the chemical and mineralogical composition of the Koolau clay can be best explained by weathering of a basaltic lava within the range of those already known in the Hawaiian Islands.

The more important changes in the formation of clays in general, of these clays in particular, and of soils commonly formed at low levels in Hawaii, are shown graphically in Fig. 11. A clay may be defined as a residue, leached of oxides of calcium, magnesium, potassium and sodium, and consisting of those oxides which possess ceramic qualities, silica and alumina, and with iron oxides largely removed. In these clays an important amount of titania must be included with the silica and alumina as the ceramic residue. In the diagram, ceramic clays fall near the top. The igneous rocks, ranging from acid to basic compositions, fall in a nearly vertical zone left of the center line. Change from the composition of a granite to a clay involves a comparatively slight relative loss of alkali and alkaline earth oxides, a slight increase and change in the proportions of silica and alumina, and usually some increase of iron. Basalt, as a producer of ceramic clay, starts with the handicap of containing much less silica and alumina, several times as much iron and twice the percentage of alkali and alkaline earth oxides as an ordinary granite. Furthermore, basalt is a fine-grained rock; there is no segregation of its feldspars or other favorable clay sources, as in some pegmatites of granitic composition. And finally, in the ordinary lowland climatic zones of Hawaii, weathering forms lateritic types of soils which contain far too

⁴³ *Loc. cit.*, 421-429 (1898).

⁴⁴ *Loc. cit.*, 6 (1917).

⁴⁵ *Loc. cit.*, 351 (1926).

⁴⁶ Washington, H. S., *Petrology of the Hawaiian Islands*, II. Hualalai and Mauna Loa: *Am. Jour. Sci.*, **6**, 108 (1923).

much iron to have any ceramic value. Production of a ceramic clay with a content of silica, alumina and titania quite within the clay range on the diagram of Fig. 11 evidently represents a type of weathering differing strongly from the common laterization and a somewhat extreme degree of such weathering. The crucial difference between this weathering and laterization is in the removal of iron, as distinguished from its accumulation.

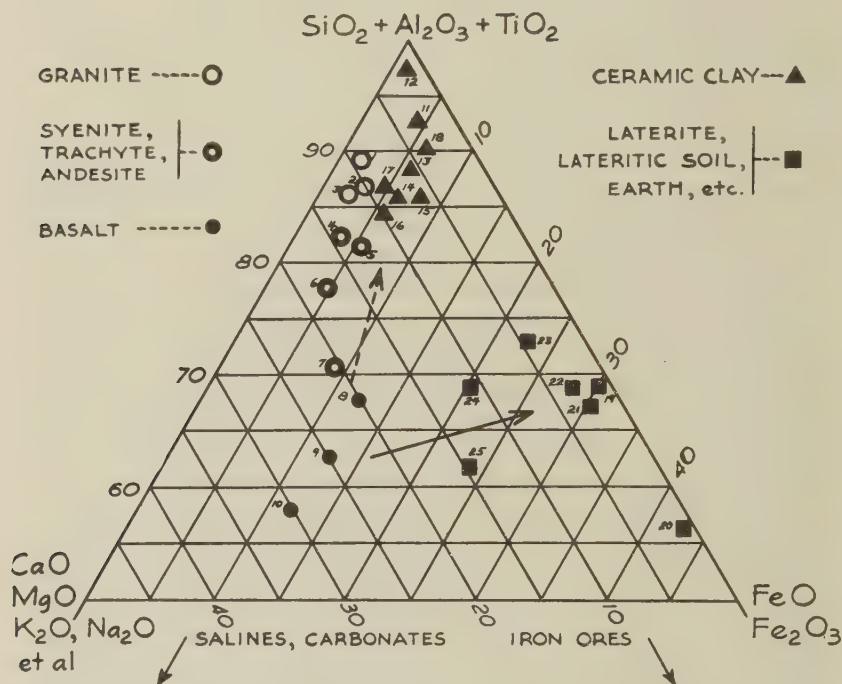


FIG. 11. Three-component diagram showing chemical composition of various igneous rocks, of Hawaiian and other clays, and of Hawaiian rocks and their more common soil derivatives. The solid arrow indicates the direction of lateritic weathering and the dashed arrow shows the contrasted direction of weathering by which the Koolau and other Hawaiian ceramic clays must have been formed. Source data are tabulated below.

- 1—Granite, Pikes Peak (Clarke, p. 441, B)
- 2—Granite, Minnesota (Clarke, p. 441, E)
- 3—Granite, Vermont (Clarke, p. 441, D)
- 4—Trachyte, Yellowstone (Clarke, p. 443, C)
- 5—Trachyte, West Maui, Hawaiian Islands (Cross, p. 47, 1)
- 6—Syenite, Montana (Clarke, p. 443, K)
- 7—Andesite, Yellowstone, (Clarke, p. 458, C)
- 8—Basalt, Koolau Range, Oahu, Hawaiian Islands (Cross, p. 48, 19) (See Table No. 1, A)
- 9—Basalt, Kauai, Hawaiian Islands (Cross, p. 48, 26)

- 10—Basalt, Puna, Hawaii Island (Cross, p. 48, 41)
 - 11—Crude kaolin, Virginia (Ries, p. 321, VIII)
 - 12—Fire clay, Alabama (Ries, p. 336, I)
 - 13—Stoneware clay, West Virginia (Ries, p. 342, VII)
 - 14—Sewer-pipe clay, Ohio (Ries, p. 346, I)
 - 15—Bentonite, Alberta (Ries, p. 369, IV)
 - 16—Crude clay, Oahu, Hawaiian Islands (Wells, this paper, 1)
 - 17—Crude clay, Oahu, Hawaiian Islands (Wells, this paper, 2)
 - 18—Crude clay, Oahu, Hawaiian Islands (Wells, this paper, 7)
 - 19—Primary laterite, British Guiana (Harrison, p. 13)
 - 20—Ferruginous bauxite, British Guiana (Harrison, p. 17, III)
 - 21—Red lateritic soil, Oahu (Kelley *et al.*, p. 27, 5) (See Table No. 1, B)
 - 22—Brown lateritic soil, Maui (Kelley *et al.*, p. 23, 547)
 - 23—Black soil, Oahu (Kelley *et al.*, p. 27, 11)
 - 24—Brown soil, Oahu (Kelley *et al.*, p. 28, 398)
 - 25—Red soil, Oahu (Kelley *et al.*, p. 29, 331)
- Clarke, F. W., Data of Geochemistry: *U. S. Geol. Survey, Bull.* **770** (1924).
- Cross, W., Lavas of Hawaii and their Relations: *U. S. Geol. Survey, Prof. Paper* **88** (1915).
- Ries, H., *Clays*, John Wiley & Sons (1927).
- Harrison, J. B., The katamorphism of igneous rocks under humid tropical conditions: *Imperial Bureau of Soil Science, Harpenden* (1933).
- Kelley, W. P., McGeorge, Wm., and Thompson, Alice R., The soils of the Hawaiian Islands: *Hawaii Agricultural Experiment Station, Bull.* **40** (1915).

SPECULARITE-ALUNITE MINERALIZATION AT HICKEYS POND, NEWFOUNDLAND*

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INTRODUCTION

During the investigation of a deposit of specularite at Hickeys Pond, in southeastern Newfoundland, in the summer of 1938 for the Geological Survey of Newfoundland, alunite was found as an abundant associate of the specularite. In a review of the literature no example of a similar occurrence was found and this deposit is therefore of particular interest in connection with the origin of alunite, a subject of considerable discussion.

GENERAL GEOLOGY

Hickeys Pond lies about 5 miles west of the head of Placentia Bay, in southeastern Newfoundland. The nearest settlements are the small fishing villages on Barren Island and Woody Island along the west side of the bay. Hickeys Pond is reached by a trail from La Plante, a small cove between these two islands. In the vicinity of the pond the country has low relief, its rolling surface dotted with numerous small bogs and ponds. Hickeys Pond, three-quarters of a mile long and less than a quarter of a mile wide, is one of the largest of these. To the north and north-east, about 2 to 3 miles from the pond, the country becomes rougher and rounded hills rise several hundred feet above the level of the lower country.

Southeastern Newfoundland is composed chiefly of pre-Cambrian rocks with isolated patches of Cambrian and Ordovician sediments fringing the bays that deeply indent the coast. The oldest pre-Cambrian rocks are the Harbour Main volcanics, a thick series of basic and acidic flows, tuffs and breccias. These are succeeded by 25,000 to 30,000 feet of slates, quartzites, sandstones and conglomerates, known as the Avalonian series. Intrusive into the volcanics and the lower members of the Avalonian series in the neighborhood of Conception Bay, is a granitic batholith, the Holyrood granite, and associated minor bodies.¹ At St. Lawrence, on the southern end of the Burin Peninsula, post-Cambrian granite, probably Devonian in age, is intruded into the Avalonian and Cambrian rocks.²

* Published with the permission of the Newfoundland Government Geologist.

¹ Buddington, A. F., Pre-Cambrian rocks of southeast Newfoundland: *Jour. Geol.*, **27**, 449-479 (1919).

² Snelgrove, A. K., Mines and mineral resources of Newfoundland: *Newfoundland Geol. Survey, Information Circular No. 4*, 27 (1938).

The pre-Cambrian has been thrown into a series of folds, the axes of which strike northeasterly. Cleavage is well developed in many of the shaly formations and the sandstones have been altered to quartzites in many places. Hickeys Pond is on the contact between a granitic mass to the northwest and greenstone and schist to the southeast. The border facies of the intrusion is granodiorite, but the exact composition of the rock nearer the center of the intrusion (that is, farther northwest) is not known. The contact between the granodiorite and metamorphic rocks strikes about N. 40° E. in the vicinity of the pond but is not a straight line, nor is the contact sharp, as the schist is granitized near the contact. Areas of schist are included within the main granodiorite mass, and outcrops of granodiorite and thoroughly granitized schist occur within the main schist area.

The metamorphic rocks comprise massive greenstones, schistose greenstones with agglomeratic facies, talc schists, and quartz-sericite schists. Metamorphism has obscured the original character of the rocks, but their composition and the presence in places of bedded agglomeratic facies points to a series of basic lavas, tuffs, and agglomerates.

The greenstones are made up of quartz, chlorite, sericite and epidote, with minor amounts of magnetite and apatite. Some facies contain hornblende. In the schistose varieties the chlorite and sericite are well aligned. Quartz is in small evenly distributed grains in most specimens, but in a few there are scattered large grains. Feldspar was not detected, though it may be present in the fine-grained groundmass. Epidote is in patches, or more characteristically, in veinlets which can be detected as streaks of yellowish green in the darker green of the massive varieties. Hornblende is in long laths. Agglomeratic facies are well developed in places and provide the only evidence of sedimentary origin. They are dark mottled green with abundant pebbles as large as an inch in diameter.

Talc schist and quartz-sericite schist are common and often associated with each other. Since the talc schist is soft and readily eroded it is responsible for falls in many places where streams flow across it. The lip of the falls may be massive or granitized greenstone, or resistant quartz-sericite schist associated with the talc schist.

The strike of the schistosity ranges from N. 5° E. to N. 60° E., averaging about N. 30° E. It everywhere dips between 60° and 80° NW. Where bedding is apparent, as in the agglomerates, it is parallel to the schistosity.

The granodiorite is a pink, medium-grained, granitoid rock. Biotite is the common dark mineral, but there are some hornblende-bearing facies. The granodiorite shows a clear orientation of minerals in many

places. Near the contact with the schist, the average strike of the orientation, with some local variation, is N. 30°–40° E., with a steep dip to the northwest. Away from the contact the orientation averages about N. 5° W. This change seems not to be gradual, but to be due to shearing in a N. 40° E. direction near and parallel to the contact, superimposed on and obscuring what is probably an original N. 5° W. orientation. In places near the contact the granodrite is much sheared; elsewhere, although it appears unsheared megascopically, the microscope reveals strain shadows and mortar structure in the quartz. Diabase dikes, in some cases badly sheared to greenstones, are very abundant, but confined mostly to the granodiorite. A few occur in the contact zone. The strikes of most of them lie between N. 5° and N. 15° W.

At some time following the intrusion of the granodiorite there were strong shearing movements. In the greenstone these produced chlorite schist, or, in extreme cases, talc schist. In granitized areas where the composition of the rocks was more acid, the result has been quartz-sericite schist. Although outcrops of schist cannot be followed continuously, both the talc and sericite schists are found along a line near and parallel to the contact between granodiorite and volcanics. All of them lie near a line about six miles long connecting the two most widely separated zones. The major shear, then, was confined to this zone, striking N. 40° E. parallel to the contact, and might be thought of as a fault, although the total displacement along this zone is not known. It was perhaps not very great. The latest movement, as determined from a drag in a quartz vein close to a schist outcrop at Hickey's Pond, shows a downward movement of the southeast side.

Neither the age of the volcanics nor that of the granodiorite is known. The whole of the peninsula between Placentia Bay and Fortune Bay was originally mapped as pre-Cambrian by Murray and Howley³ and is so shown by Snelgrove.⁴ If the volcanic rocks are pre-Cambrian, they would probably be correlated with the Harbour Main formation of the Avalon Peninsula. Although the volcanics have not been traced south-eastward across their strike, the rocks near the Placentia Bay shore are dark gray to brown slates, possibly belonging to the Conception slate of the Avalonian series. Recent work on the north shore of Fortune Bay, however, has brought to light the existence of a thick series of volcanics overlying the Cambrian, containing both acidic and basic

³ Murray, Alexander, and Howley, J. P., Geological survey of Newfoundland from 1864–1880, *Stanford*, London (1881).

⁴ Snelgrove, A. K., Mines and mineral resources of Newfoundland: *Newfoundland Geol. Survey, Information Circular No. 4*, pl. 2 (1938).

lavas.⁵ Until further work is done, connecting the Hickeys Pond area with the Fortune Bay area, the possibility that the Hickeys Pond volcanics are Paleozoic is not excluded.

The age of the granodiorite may also be Paleozoic. Hickeys Pond lies between the Devonian granite of St. Lawrence and the pre-Cambrian granite of Conception Bay, and it is not at the present time possible to say with which it is correlative.

SPECULARITE-ALUNITE MINERALIZATION

The only abundant specularite-alunite mineralization is at Hickeys Pond, although small disseminations were found at two other places, 2 miles to the northeast and $2\frac{1}{2}$ miles to the southwest, along the shear zone.

Hickeys Pond is nearly cut in half by a peninsula which extends about 500 feet into the pond from the southeast side and is 900 feet wide. The peninsula has a rounded dome-like surface rising to a maximum elevation of 60 feet above the surface of the pond. About a quarter of the peninsula is a smooth bare outcrop and the rest is covered only with moss or a thin soil. The neck of the peninsula is low with no outcrops, but immediately to the southeast are exposures of white sericite schist.

The rock of this peninsula is silicified schist and its resistant character is undoubtedly responsible for its not having been eroded by the glacial ice. Its isolated position and the absence of outcrops of similar rock in the area argue against the continuation of the deposit to the northeast and southwest under the waters of the pond. Outcrops close to the northwestern shore of the pond are granodiorite. To the southeast beyond the sericite schist is a greenstone schist, and at both ends of the pond are zones of granitized schist. This silicified body is along the contact, therefore, and represents a special case in the alteration of the volcanics by the intrusion.

The silicified rock has a gneissic structure with well-developed banding over a large part of the outcrops. The bands range from a quarter of an inch to several inches wide and are the result of the concentration in various proportions of specularite, alunite and quartz. In general the specularite and alunite vary proportionately: where there is much specularite the rock is strikingly banded in black and pink, the pink bands containing as much as 50 per cent alunite; where there is sparse specularite the banding is faint, the color of the rock is a dirty light gray, and there are only a few per cent of alunite and hematite. There is still an inherited schistose structure, however, and the sparse hematite

⁵ White, D. E., Personal communication.

is strung out parallel to the schistosity. All three minerals are fine grained (0.01–0.2 mm.) and the rock has an aplitic appearance. In addition to these minerals there are minor quantities of talc, pyrite, and an unidentified yellow mineral in very minute grains.

The quartz of the altered rock is evenly fine grained (Fig. 2). Only a few scattered grains are larger than the average range of 0.01–0.1 mm. Some of these larger grains are corroded fragments of large single grains. The quartz grains show a distinct elongation parallel to the banding of the rock. Veinlets, a millimeter or so wide, of coarser quartz cut across the banding and the grains in these also show elongation parallel to the banding and at an angle to the direction of the vein.

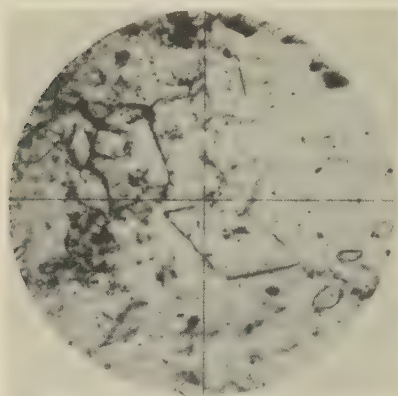


FIG. 1. Photomicrograph of a thin section showing alunite and a few grains of hematite in a groundmass of quartz. The large diamond-shaped alunite crystal near the center illustrates a common habit. In the upper left quadrant is a smaller grain with the basal pinacoid well developed. One nicol, $\times 51$.

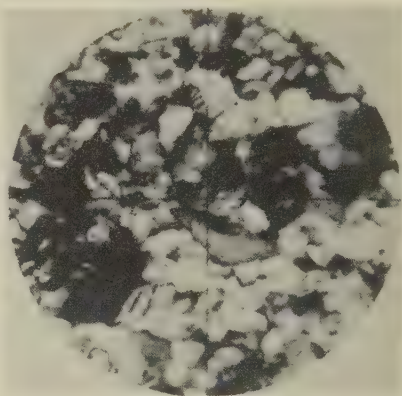


FIG. 2. Photomicrograph of the section shown in Fig. 1 taken with crossed nicols to show the texture of the quartz in the replaced rock. $\times 44$.

The alunite commonly has good euhedral development. The common form is a rhombohedron, which appears as diamond-shaped crystals in a thin section (Fig. 1). The basal pinacoid is not uncommon, truncating the obtuse angle of the diamond. The basal cleavage and long dimension of the diamond-shaped cross sections are commonly parallel to the banding. Hexagonal cross sections also occur. The mineral is uniaxial positive, $\omega = 1.578$, $\epsilon = 1.601$, both $\pm .003$. It yields acid water in the closed tube and gives positive tests for aluminum and alkalis.

Specularite, as seen in thin and polished sections, occurs in ragged masses or individual grains and blades. With dark-ground illumination

the granular character of the ragged masses can be clearly seen in polished sections. The specularite is distributed parallel to the banding, its blades oriented in the same direction.

Minute crystals of an unidentified yellow, anisotropic mineral with high indices of refraction are scattered through the rock and are closely associated with, or included in, the alunite. The crystals range in size from 0.005–0.02 mm. and are in most cases equidimensional, but there are a few slightly elongated prismatic forms. The habit resembles that of zircon, but larger identifiable zircon grains in the same rock have a somewhat lower relief and are colorless. The habit and relief do not correspond with those of jarosite. Turner⁶ described minute brownish-red anhedral inclusions in the alunite of an altered andesite tuff at Tres Cerritos, California. An analysis of the alunite showed 0.40 per cent of TiO_2 and chemical tests on some of the separated grains showed they were rich in TiO_2 and were the probable source of that oxide in the analysis. Turner suggested that possibly the mineral was rutile, and this also seems the most probable identification for the Hickeys Pond mineral.

Pyrite in small crystals occurs chiefly in the specularite-poor silicified schist and is absent in most of the strongly alunitized and specularitized rock. Well-developed "pressure-shadows" occur around many pyrite grains. Plates of talc parallel to the banding are localized near the quartz vein to be described below.

Near the center of the peninsula there are numerous large quartz veins penetrating the silicified rock, striking N. 65° E. and dipping steeply NW. parallel with the banding. The contact of the vein zone to the southeast is sharp against the silicified schist. The latter is much contorted and in the contact there is a big roll, or drag fold, about 8 feet across, showing downward movement of the footwall. A zone of talc 2 or 3 inches wide follows the contact, and talc is present in masses an inch or so across in the edge of the quartz vein. In the 2 or 3 feet of the vein nearest the contact there are large masses of bladed specularite ranging in width from half an inch to 6 inches, and in length from a few inches to 4 feet. They have an average strike of N. 5° W., and dip 84° W. To the northwest of this specularite zone is a mass of barren white quartz, 8–9 feet wide, enclosing blocks and lenses of silicified schist. Beyond this for 20 feet the schist predominates and quartz veins are fewer until they die out entirely. Along the strike this wide zone of quartz veins narrows rapidly, and 250 feet to the northeast is represented only by a vein 3 feet wide with specularite blades up to a quarter of an inch in length.

⁶ Turner, H. W., Rocks and minerals from California: *Am. Jour. Sci.* (Series 4), 5, 424–425 (1898).

Beyond this point the veins were not seen. A few small quartz veins occur elsewhere on the peninsula, but are barren of specularite and in most cases are in the siliceous non-specularitic rocks. The quartz of the veins is in large grains with no evidence of crystal form. It shows strong strain shadows and incipient granulation. A few euhedral crystals of alunite can be found by microscopic study.

In the alteration of the original schist quartz is the earliest mineral formed. Hematite blades cut across the quartz grains and are in part later than the quartz. Alunite includes grains of hematite and thus seems to be somewhat later. Pyrite is definitely later than the specularite, since cubes of the former cut across the specularite bands, but its relation to alunite is not clear, as it is chiefly developed where the alunite is sparse. The plates of talc in the schist contain a few nests of alunite crystals which are probably later, having penetrated along the cleavages.

Two localities with minor amounts of mineralization lie in line with Hickeys Pond along the shear zone. At Chimney Falls, $2\frac{1}{2}$ miles to the southwest on Hickeys Brook, specularite is disseminated in a zone 8 feet wide in streaks parallel to the folia of the talc schist below the falls. Thin specularite bands are spaced from an eighth to a quarter of an inch apart. Quartz veins with specularite occur in this zone, most of them only 1 to 2 inches wide, but one lens measuring $1\frac{1}{2}$ feet across and 4 feet long contained alunite as well as fine-grained specularite. There has been very little silicification of the schist. On the schist planes the hematite has been sheared and slickensided.

Two miles to the northeast of the pond, Hickeys Brook crosses a chlorite-talc schist that is pyritized and cut by a few quartz stringers and lenses an inch or so wide containing a little fine-grained specularite. The schist zone is about 200 feet wide. The pyrite in the talc schist has been slickensided in the same fashion as the specularite at Chimney Falls.

It is clear that there has been movement and shearing since the alteration of the schist and injection of the quartz veins. The elongation of the quartz grains of the gneiss indicates recrystallization under stress, and so does the parallelism in the elongation of the quartz grains in the cross-cutting veinlets. Well-developed "pressure-shadows" of elongated quartz blades radiate from around pyrite grains. The specularite shows the same phenomenon, although less commonly, due to its rarer occurrence in large, strong grains. Specularite and pyrite have been slickensided. The large quartz vein at Hickeys Pond with the roll or fold in it, and the massive white quartz showing strong strain shadows and incipient granulation lend further support to the inference that some deformation followed mineralization.

The history of events, then, may be interpreted as follows:

1. Intrusion of granodiorite into greenstone with accompanying granitization. The contact runs roughly parallel to the structural trend of the region, about northeast.

2. Shearing along a zone which is parallel and close to the granodiorite-greenstone contact. The greenstones were changed to chlorite and talc schists, and the granitized rocks altered to quartz-sericite schists.

3. Silicification, specularitization and alunitization in zones determined by these shear zones. Where the mineralization was intense the schists were completely altered to a gneissic rock. Elsewhere specularite was the chief mineral introduced along the schist planes. The formation of the quartz veins was associated with this mineralization. The well-crystallized talc along the footwall of the large vein may be material absorbed from the schists and recrystallized near the wall of the vein.

4. Further movement along the shear zone folded the quartz vein and crumpled the silicified schist southeast of the footwall. The fine-grained quartz of the gneiss was recrystallized and elongated and the quartz of the cross-cutting veinlets was oriented in the same direction. The pyrite and specularite in the talc schist were sheared and slickensided.

PROBLEM OF ALUNITIZATION

Alunite is a characteristic product of solfataric action and is found as an alteration of acidic or intermediate lavas in many places. Silicification and the formation of kaolinite, or occasionally diaspore or bauxite, are usually associated with it. This view of its origin is supported by the known occurrence of sulphur dioxide as a constituent of the gasses of solfatara and the wide-spread occurrence of alunite in lavas.

De Launay,⁷ however, presented good reasons for believing that the deposits at Tolfa, Italy, were due to the oxidation of pyritic veins in trachyte and the reaction of the sulphuric acid thus produced with the feldspar of the trachyte. In support of this he pointed out the deep ground water circulation, the passage of alunite veins into pyrite veins below the level of active circulation, and the gradation laterally of alunite into kaolinite, the normal weathering product of the trachyte, beyond the zone of pyrite concentration.

At Cripple Creek alunite and kaolinite are found only in the oxidized zone and probably have an origin similar to that of the Tolfa deposits.⁸

⁷ De Launay, L., *La metallogenie de l'Italie: Compt. Rend., X Internat. Geol. Cong., Mexico*, 1, 679-686 (1907); quoted in translation by Butler, B. S., and Gale, H. S., *U. S. Geol. Survey, Bull.* 511, 51-55 (1912).

⁸ Lindgren, Waldemar, and Ransome, F. L., *Geology and gold deposits of the Cripple Creek district, Colorado: U. S. Geol. Survey, Prof. Paper* 54, 125 (1906).

At Goldfield, Nevada, alunite is one of the most characteristic minerals of the gold deposits and occurs both as a widespread rock alteration and as a vein mineral, closely associated with gold and sulphides. Ransome⁹ discussed the origin of the alunite in detail. He dismissed the hypothesis that the alunite was formed from the oxidation of pyrite because of its quantitative insufficiency: there were no large sulphide bodies which could have produced sulphuric acid in the amount necessary to cause such widespread alteration. He also pointed out that alunite occurred 500 feet below the bottom of the weathered ores and was crystallized with pyrite throughout the rocks. Objections to a direct volcanic origin are less specific and refer to the improbability of the presence of sulphates in magmatic waters. The rarity of sulphate minerals as compared with sulphides, and of alunite in particular in metalliferous veins, and the absence of sulphuric acid in most hot springs are points favoring this improbability. Moreover, it is questionable whether waters rich in sulphuric acid would be efficient carriers of gold, sulphides and tellurides. He therefore concluded that hydrogen sulphide in rising solutions was oxidized near the surface to sulphuric acid and was recirculated downward, where it caused the precipitation of sulphides and the simultaneous formation of alunite.

The Goldfield district is apparently unique in the occurrence of alunite in the gold and sulphide-bearing veins. Elsewhere, however, alunite is not associated with sulphide minerals, other than pyrite, and it has been suggested that rising solutions carried the sulphate radical. In the San Cristobal quadrangle, Colorado, Larsen¹⁰ found large masses of lavas, a square mile in area and extending 2000 feet vertically, altered to quartz and alunite with minor amounts of kaolinite, bauxite, and pyrite. The large volume of alteration, the absence of other oxidation products, the presence of pyrite, and the occurrence of hinsdalite ($2\text{PbO} \cdot 3\text{Al}_2\text{O}_3 \cdot 2\text{SO}_3 \cdot \text{P}_2\text{O}_5 \cdot 6\text{H}_2\text{O}$) in a nearby quartz-sulphide vein are all in favor of hot ascending sulphuric acid solutions. However, in view of the fact that such solutions were not generally thought by geologists to exist, Larsen did not think the evidence was sufficient to justify such an explanation, and gave as an alternative source for the alunite the mingling of hot ascending solutions or gasses carrying hydrogen sulphide with surface oxidizing waters.

The possibility of sulphuric acid in ascending waters received dis-

⁹ Ransome, F. L., The geology and ore deposits of Goldfield, Nevada: *U. S. Geol. Survey, Prof. Paper* 66, 129-133, 189-195 (1909).

¹⁰ Larsen, E. S., Alunite in the San Cristobal quadrangle, Colorado: *U. S. Geol. Survey, Bull.* 530, 179-183 (1913).

cussion and support by Butler and Gale¹¹ in their study of the deposits of alunite at Marysvale, Utah. The veins in the district are described as quartz-carbonate veins, many of them containing adularia and minor amounts of sulphides, sulpho-salts, etc. Exceptionally they contain alunite. In addition there are veins in which the filling is chiefly alunite. Alunite is an alteration in the wall rock of the veins and is sufficient in amount to account for the original potassium and aluminum content of the rock. The alunite of the veins must, therefore, be introduced from some distance. Moreover, adularia in the quartz-carbonate veins indicates that the hot ascending waters which formed them contained potassium and aluminum. Butler and Gale concluded that the alunite veins were deposited by ascending solutions. At what stage the sulphuric acid was formed could not "be positively stated, but it seems most natural to suppose that it was a part of the original solutions and that the potassium and aluminum were in part original in the solution and in part dissolved from the walls of the fissure at greater depth."¹²

At Hickeys Pond the origin of the alunite is clearly not due to the oxidation of pyrite. The outcrops are all polished glaciated surfaces and recent weathering is of the slightest. Furthermore, there are no large quantities of pyrite available.

The deposit has the appearance of being formed at a greater depth than any of the deposits described above. Butler and Gale¹³ believed that the alunite deposits were formed near the surface, although of hypogene origin. Here, however, there is an absence of porosity or any cavities, the replacement has been complete, and the original texture has been obliterated except for the preservation of the earlier schistosity in the form of a gneissic banding. Movements along the shear zone after mineralization have the characteristics of shear at some depth rather than those of fault breaks at shallow depth. The sharp folding without brecciation of a massive quartz vein may be referred to in this connection.

Sulphates such as barite, celestite, anhydrite and hinsdalite (a member of the alunite group) are known to occur as primary minerals in veins of hypogene origin, and that the sulphate radical is even present in certain magmas is shown by its presence in minerals such as noselite, haiynite, lazurite and microsommite. Under what conditions sulphate may be present is not clear. The insolubility of such sulphates as barite make it seem probable that the barium is carried in some more soluble

¹¹ Butler, B. S., and Gale, H. S., Alunite, a newly discovered deposit near Marysvale, Utah: *U. S. Geol. Survey, Bull.* 511, 21-37 (1912).

¹² Butler, B. S., and Gale, H. S., *op. cit.*, 36.

¹³ *Ibid.*, 36.

form, such as the chloride and precipitated rapidly when the sulphate radical makes its appearance. The same is likely to be true of alunite. The oxidation of sulphur to sulphate by the reduction of iron is apparently not a possible process at Hickeys Pond as the iron is all in the form of hematite. Solutions rich in oxygen possibly were the agents in this case, with the formation of sulphate at a deeper stage than is common. The oxidation of the sulphur is not complete, however, as there is some pyrite. As an alternative it may be suggested that the precipitation of alunite is due to the penetration of oxidized waters from the surface and their mingling with the rising solutions, although the absence of other oxidation products throughout the shear zones, mineralized or not, is unfavorable to this.

ECONOMIC POSSIBILITIES

The possibility of production of iron ore at Hickeys Pond is slight. The specularite in the quartz veins is restricted to a width of two feet and is not persistent along the strike. The gneissic specularitized rock is very low grade. Two channel samples of some of the most highly specularitized rock, assayed by the Newfoundland Government Laboratory, showed 3.42 and 2.87 per cent iron.

Small quantities of alunite have been mined as a source of potash at Tolfa, Italy, for more than 100 years. At various times production has been reported from Canada, Australia, Russia and Japan. In recent years large tonnages have been produced in Chosen (81,510 metric tons in 1935)¹⁴ and in Spain (23,985 metric tons in 1931),¹⁵ although the potash content of this material is not known. Alunite was mined at Marysvale, Utah, during the war, and a small quantity is still shipped every year for crushing and direct application as fertilizer, and for experimental purposes.

Alunite is also a possible source of alumina and sulphuric acid, although to date these have not been extracted commercially. Indeed, Hedges states that normally alunite "merits consideration only as an ore of aluminum, with potash as a valuable byproduct. Until such time as shifting markets, technologic improvements, exhaustion of cheaper source materials, or other changing conditions bring about utilization of alunite for production of aluminum, no important quantity of potash will be derived from this source."¹⁶

Both the Tolfa and Marysvale deposits are nearly pure alunite, but estimates at Marysvale showed that with high shipping costs the margin

¹⁴ Minerals Yearbook, 1938, *U. S. Bur. Mines*, 1248 (1938).

¹⁵ Minerals Yearbook, 1936, *U. S. Bur. Mines*, 1018 (1936).

¹⁶ Minerals Yearbook, 1936, *U. S. Bur. Mines*, 1013 (1936).

of profit was small.¹⁷ At Hickeys Pond the low content of alunite in the mineralized rock is not encouraging for development. No analytical data are available, but 20 per cent of alunite in the rock is a generous estimate, for although specimens were noted which contained as much as 50 per cent, a good deal of the mineralized area contains only sparsely disseminated alunite.

¹⁷ Waggaman, W. H., and Cullen, J. A., The recovery of potash from alunite: *U. S. Dept. Agr., Bull.* 415, 12-13 (1916).

PEGMATITE DIKES OF THE BRIDGER MOUNTAINS, WYOMING*

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ABSTRACT

The central area of pre-Cambrian rocks in the Bridger Range of central Wyoming consists predominantly of black hornblende schist. The schist has been invaded by large masses of coarsely crystalline granite. The granite invasion was followed by two distinct intrusions of granite pegmatite. The older pegmatite dikes were intruded along a steeply-dipping joint set which is parallel to the plane of foliation of the schist. The younger pegmatite dikes have a lesser dip and were intruded along a joint set which was formed subsequent to the intrusion of the older dikes.

The intrusion of the older dikes was followed by an invasion of silica-rich and potash-rich hydrothermal solutions which replaced the black schist with quartz and sericite. The intrusion of the younger dikes was followed by an invasion of hydrothermal solutions which partially replaced the original dike minerals and precipitated cleavelandite, muscovite, tourmaline, beryl, garnet, columbite, tantalite, chalcopyrite, lepidolite and petalite.

* A portion of a Ph.D. thesis, University of Kansas, 1939.

Several of the hydrothermal minerals were deposited in parallel bands which strike and dip nearly parallel to the strike and dip of the dikes. The semi-concentric arrangement of these bands and their uniform parallel arrangement indicates a rhythmic precipitation similar to "Liesegang rings."

After a removal of the overburden by erosion, several supergene minerals were formed, including quartz, sericite, malachite and limonite.

The purpose of this study was to determine the history of the country rock, the structural relationships between the dikes and the country rock, the relative ages of the two types of dikes, and the paragenesis of the minerals within the dikes.

INTRODUCTION

The area which was studied lies in the northeast part of Fremont County near the center of the state. The pegmatite dikes that were mapped are intruded into the pre-Cambrian rocks east of the Wind River Canyon. They are 15 miles northeast of Shoshoni and about 20 miles southeast of Thermopolis. Field studies were made during the summers of 1936, 1937, and 1938, and were supplemented by laboratory work in the spring of 1937 and the fall and winter of 1938.

A map of sections 27 and 28, range 93 west, township 40 north, was made by a plane table survey in which both the geology and topography were mapped. The map shows the topography, with a contour interval of 20 feet, and the areal geology. Rock types mapped include the pre-Cambrian schist, pegmatite dikes, and Pleistocene (?) alluvium.

I wish to express my sincerest thanks to K. K. Landes and H. T. U. Smith for the help rendered in the field, in the laboratory, and in the theoretical discussions. Mr. LeRoy Fugitt, Mr. Bruce F. Latta, and Mr. Kenneth E. Corr assisted in the field work during the summers of 1936, 1937, and 1938, respectively. Mr. Ed Crabb and Mr. Denny Thoren of Shoshoni and Mr. Val B. Maghee of Lander furnished valuable information about the area studied.

The first mining in this area was done in 1906 when Mike Crowley filed a claim in dike 85. Some mica was taken out, but the project was soon abandoned. The present claimants, Jake Stephenson and others, filed in 1910 and mined a small amount of feldspar, beryl, and mica in dikes 3, 7, 25, 81, and 85. One of the claimants leased and did some work on dike 7 in 1928, taking out feldspar and lepidolite. The claims at present are leased by Mr. Val B. Maghee of Lander, Wyoming, who has been working on dike 86 since early in 1937 and has marketed several hundred pounds of tantalite. He is also mining beryl from the same dike.

GEOLOGIC MAP

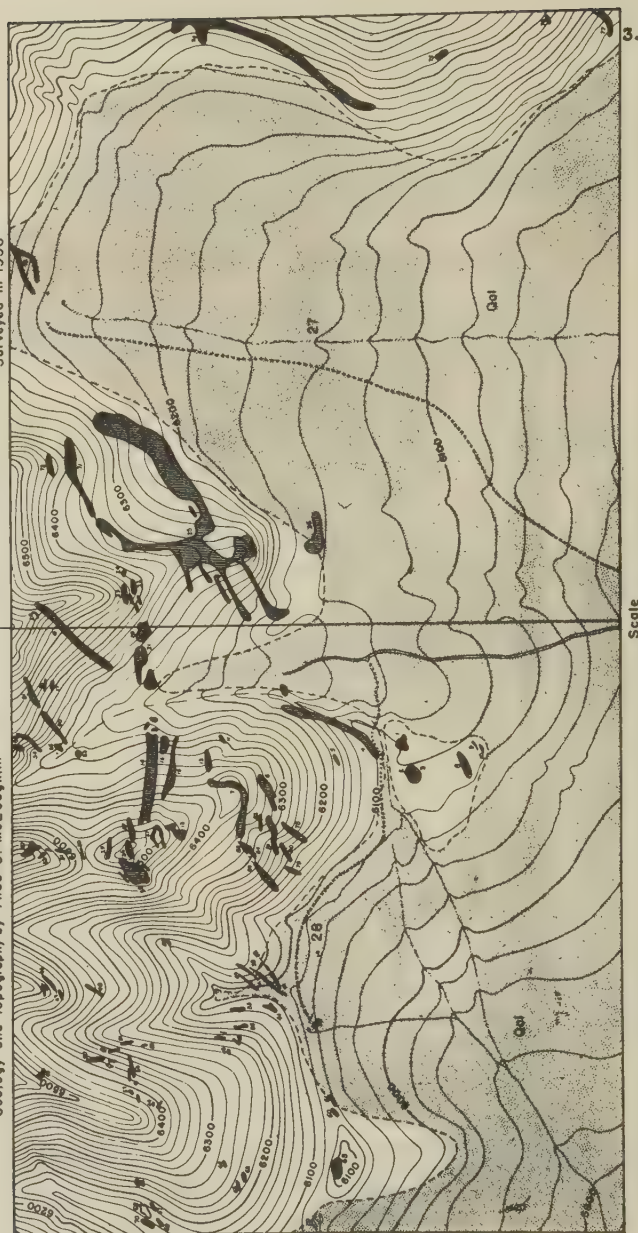
Secs. 27 and 28, T. 40N., R. 93W.

Fremont County, Wyoming

Geology and topography by Thad G. McLaughlin

EXPLANATION

- Quaternary alluvium
 — Usable road
 - - - - - Wagon trail
 □ Pagmatite dikes and number
 □ Pre-Cambrian schist
 Contour interval 20 feet
 Surveyed in 1936



COUNTRY ROCK

PRE-CAMBRIAN

AREA

The pre-Cambrian rocks outcrop in a roughly triangular area nearly 20 miles long and 10 miles wide, elongated in an east-west direction. They are also exposed several miles west of this area in the bottom of Wind River Canyon in a triangular area 1 mile wide and $1\frac{1}{2}$ miles long (6).

DESCRIPTION

The black country rock is a fine grained schist composed dominantly of hornblende and labradorite. The schist resembles a fine grained igneous rock, but the crystals are elongated parallel to the schist's foliation. Thin sections of the country rock show that it is a hornblende schist.

Hornblende constitutes 70 to 85 per cent of the schist. It occurs in elongated lath-like subhedral crystals, which are crossed and interpenetrating. The color in thin section, because of strong pleochroism, varies from light to medium blue-green. The laths are 0.1 to 0.5 of a millimeter long and generally about one-fifth as wide. A few crystals of hornblende are slightly altered to chlorite. The labradorite variety of plagioclase feldspar constitutes 10 to 20 per cent of the black country rock. It forms irregular masses and subhedral crystals with prominent albite twinning lines. It is colorless and has a low relief and low birefringence. The individuals were generally 0.8 to 1.0 mm. in diameter. Common accessory minerals are magnetite, chlorite, quartz, actinolite and zircon. None of these minerals ever constitute over two per cent of the rock. Magnetite forms very irregular masses which are subrounded, tabular, or trellis-like. It is often slightly altered to hematite and limonite which are nearly opaque to transmitted light, but are reddish brown to ocher yellow in reflected light.

Many thin sections of the country rock contain a very fibrous or asbestiform mineral, which is probably an alteration of hypersthene to actinolite. The fibers are very coarse and irregular to wavy. Pleochroism is very strong, with a color variation from pale grayish brown to brownish black. The birefringence is high, but the colors are slightly obscured by the color of the mineral. Zircon is present in every thin section that was made of the country rock. It may be rounded, ellipsoidal, or rod-like with rounded ends. The extinction is parallel, the relief and birefringence are very high, and the color is gray to colorless.

The granite outcrops in the eastern third of the pre-Cambrian area. It is a medium to coarse-grained rock containing over 90 per cent pink

feldspar with only a small amount of quartz and muscovite. Near the granite-schist contact the granite has a gneissic structure and a much greater percentage of muscovite and quartz. Joints extend from the granite into the schist without offset. The granite erodes into rounded knobs and hills of small relief. Granite also outcrops in Wind River Canyon (6) and near Birdseye.

STRUCTURE

The schist in this area has very distinct foliation and jointing. The strike and dip of the foliation of the schist varies considerably from one locality to another. The strike is "not more than 10° from east to west" in Wind River Canyon (6 p. 1419), but in the two sections that were mapped the strike varied from S. 40° W. to S. 83° W. with an average of S. 60° W.

The dip of the foliation in Wind River Canyon ranges from 30° to 60° S. with an average of 45° S. (6 p. 1419) while in the area that was mapped, the average dip was 66° S. with a maximum of 70° S. and a minimum of 58° S. The jointing in the schist dips against the foliation of the schist. The dip varies from 40° to 50° N. with an average of about 45° N. It is along these joints that many of the pegmatite dikes were intruded. The granite in the eastern part of the pre-Cambrian area, and many of the larger pegmatite dikes, also show distinct jointing.

HISTORY

A considerable controversy has taken place concerning the origin of hornblende schist and similar metamorphic rocks. Many conclusions have been based on the presence of quartz, the range of the plagioclase feldspars, and the physical properties of the zircon grains.

The zircons in some hornblende schists are smoothly rounded spheroids and ellipsoids, which closely resemble the rounded grains in sedimentary rocks. It has been inferred by some that this is sufficient proof of a sedimentary origin. Later investigators have pointed out that many of the zircon grains are oblong as well as rounded, and that rounded grains can be found in igneous rocks, such as diorite, dolerite and basalt (22). Zircon crystals from the Bridger mountain schists have length to width ratios as high as 8 to 1. Grains of such shape are probably not of sedimentary origin.

Carlson (3) believes feldspar and quartz are indicators of the former character of metamorphic rocks. A narrow range in the plagioclase feldspars is indicative of an igneous origin, for derivation from sedimentary rocks would result in a wide range in plagioclase feldspars, and also an excess of quartz.

The schists of the Bridger Range contain elongate grains of zircon, have a narrow range of plagioclase feldspars, and are almost devoid of quartz. These criteria point to an igneous origin, probably from a diorite or basalt.

The red, coarse-grained granite at the east end of the pre-Cambrian area was intruded after the formation of the black schist, for it shows very few signs of regional metamorphism. One jointing system passes through both schist and granite, which means that this granite is older than the nearby pegmatite dikes which were intruded along the jointing system in the schist.

Another area of red granite is exposed near Birdseye at the Gold Nugget mine. The pegmatite dikes in this locality have been intruded into the schist parallel to the near-vertical jointing system. These dikes also intrude the red granite which is probably the source of the later pegmatite dikes.

PEGMATITE DIKES

DISTRIBUTION

The black schist in Wind River Canyon and in the pre-Cambrian area east of the canyon has been invaded by many granite pegmatite dikes. These dikes outcrop in all parts of the schist area and in the granite area near Birdseye, but none were found in the granite at the east end of the pre-Cambrian area.

The simple dikes (those which have not suffered later hydrothermal replacement) are evenly distributed throughout the area of black schist. Most of them strike and dip concordantly with the foliation of the schist, but a few in Wind River Canyon are parallel or subparallel to a joint system which dips against the foliation.

The complex dikes, all of which dip in a direction opposite to the dip of the foliation of the schist, are concentrated in a small area on the south side of the mountains in range 93 W. Most of them were included in the map of sections 17 and 28. Dike 86 is the only dike containing hydrothermal minerals that does not lie in either of these two sections. It outcrops in the southeast quarter of section 21.

AGE

The pegmatite dikes are truncated by the Deadwood sandstone in Wind River Canyon. This indicates a pre-Cambrian age for the dikes. The relationships of the pegmatite dikes and the Paleozoic sediments are not readily observable along the south side of the Bridger Range because of the extensive overlap of the Wind River formation. The writer was unable to find any dikes that were intruded into sedimentary rocks.

OLDER DIKES

DESCRIPTION

The older dikes in this area are those which strike and dip parallel or subparallel to the strike and dip of the schist's foliation. Only 19 per cent of the dikes in sections 27 and 28 are of this type. Many of these dikes are small parallel bands intruded in a lit-par-lit manner. Others are large,



FIG. 2. Older dikes intruded parallel to the foliation of the schist.

coarsely-crystalline masses. Dike 38 is 50 meters wide and 170 meters long. The large area of altered schist adjacent to this dike indicates that if the dike were entirely exposed it would be nearly 350 meters long. Nearly 50 per cent of the older dikes are more than 35 meters in length and 90 per cent of them are 20 meters or more long.

The older dikes are all elongated bodies but where insufficient country rock has been eroded from the dike the outcrop area may be roughly circular. One can roughly determine the actual dimensions of the dike, however, by measuring the length and width of the zone of altered schist

which invariably overlies the buried part of the dike. The length is always 5 to 10 times as great as the breadth.

STRUCTURAL RELATIONSHIPS

The average strike and dip of the dikes is S. 61° W. 65° S., which is almost identical to that of the foliation of the schist (S. 61° W. 66° S.). The strike of the dikes ranges from S. 40° W. to S. 80° W. The maximum dip of the dikes is 70° S. and the minimum dip is 58° S. The strike and dip of the dikes coincide much more closely with the strike and dip of the foliation in this area than they do in Wind River Canyon.



FIG. 3. Jointing in the older dikes.

CONTACT METAMORPHISM

The intrusion of the older pegmatite dikes was accompanied by alteration of a large amount of country rock. The altered zone always lies above the dike and never extends more than one meter on either side of it. Silica-rich solutions, which travelled beyond the dike itself, followed the easiest passageway, which was parallel to the foliation of the schist. Thin sections of this altered country rock show considerable change from the original hornblende schist by the addition of a large amount of quartz and some muscovite. Hornblende and plagioclase, and the accessory minerals magnetite and zircon are present. The percentage of hornblende is greatly reduced and quartz is the predominant mineral.

Megascopically, the metamorphosed schist is brown to brownish green. It is more micaceous, softer, less brittle, and can be readily distinguished from the original black schist even at a considerable distance.



FIG. 4. Pegmatite dikes in the black schist in Wind River Canyon. (Photo by H. T. U. Smith)

MINERAL DESCRIPTIONS

Microcline. The most abundant mineral in the older dikes is microcline. It constitutes more than 70 per cent of the rock which is made up entirely of quartz and feldspar. The microcline is dominantly white but may also be various shades of gray, light blue and rarely pink. It is coarsely crystalline with some individuals more than a meter in diameter. No euhedral or subhedral crystals were observed. A perthitic intergrowth of albite and microcline was found in several dikes. The color of both the albite and microcline is white, making the perthite difficult to distinguish from the specimens of pure microcline. Quartz is the most common mineral associate of microcline but tourmaline may rarely be present where a younger dike transects an older one.

Quartz. Quartz is next in abundance and constitutes almost 30 per cent of the rock in the older dikes. It is always anhedral and its color is generally pale milky but locally is dull gray. The quartz is evenly dispersed throughout the dike and is seldom concentrated in lenses as it is in the younger dikes. It frequently forms veins, varying in width from 1 to 30 cm. which penetrate the country rock in a lit-par-lit manner. These veins often contain a small amount of microcline.

Tourmaline. Black tourmaline is found in an older dike (no. 28) where it is cut by a younger dike which dips in a direction opposite to that of the foliation of the schist. The tourmaline-bearing solutions obviously came from the same parent magmas as the younger

dike. These solutions followed the sides of the younger dike and deposited tourmaline in small veins and clusters in both the older and the younger dikes. The tourmaline is found in subhedral crystals less than 2 cm. long. These elongated crystals cut both the quartz and the microcline.

YOUNGER DIKES

DESCRIPTION

The younger dikes are those that dip north against the foliation of the schist. Eighty-one per cent of the dikes that were mapped in sections 27 and 28 are of this type. These dikes outcrop only in a small area on the



FIG. 5. Sharp contact of a younger dike with the country rock.

south side of the Bridger Mountains near the contact of the black schist and the alluvium. Most of the younger dikes are elongated, tabular masses with a length 5 to 20 times as great as the thickness. The average thickness of the dikes in sections 27 and 28 is 5 meters and the average length is 84 meters. The mean ratio of length to thickness is 16 to 1. The feldspar in the dikes is white, gray, or pale blue and gives the dike a decidedly white color which is amplified by the background of black schist. This contrast of color makes the dikes visible for a great distance.

The younger dikes do not weather to any characteristic forms. There is no distinct jointing, but the dikes fracture easily causing them to erode as rapidly as the schist. The rate at which they erode is controlled by the rate of weathering of the schist.

STRUCTURAL RELATIONSHIPS

One of the outstanding features of this area is the almost perfect control on the position of the dikes exercised by the structure of the country rock. All of the older dikes strike and dip parallel to the foliation of the schist. Variations in strike and dip of these dikes is caused by variations in the strike and dip of the foliation. All of the younger dikes have been intruded parallel to the jointing in the country rock. The directions of jointing are more uniform than the foliation of the schist, therefore, the strike and dip of the younger dikes is more uniform than that of the older ones.

The maximum dip measured in sections 27 and 28 is 62° N. and the minimum is 30° N. The average of all the dips measured is 45.5° N. Eighty-five per cent of the dikes dip to the north at an angle within 40° and 50° , and 50 per cent of the dikes dip north at an angle within 3° of the mean (45.5°). The average strike of the dikes is S. 43° W. which is nearly the same as that of the foliation of the schist.

CONTACT METAMORPHISM

Metamorphic effects of igneous intrusion were noted in all but two of the younger dikes. The otherwise hard, black hornblende schist has been altered to a dark bluish-green, friable material which megascopically looks very different from the original material. The contact of the altered schist with the unaltered material is always a joint plane. The metamorphosed rocks are coated at the surface by brown iron oxides. This has probably been caused by oxidation of the iron in the schist to limonite, followed by incomplete dehydration to hematite and perhaps turgite.

Microscopic examinations of thin sections of the metamorphosed material have revealed very little mineralogical change from the original unaltered schist. It contains over 70 per cent of hornblende, 5 to 15 per cent of quartz, and lesser amounts of magnetite, actinolite, and zircon.

MINERAL DESCRIPTIONS

Microcline. Microcline is the most abundant mineral in the younger dikes as well as in the older ones, but the percentage is much smaller in the younger dikes. The microcline in these complex dikes is white to pale blue and gray. It is coarsely crystalline, some individuals being over 2 meters in diameter.

The dikes originally were intruded as liquid masses of microcline and quartz with the quartz concentrated in irregular lenses at the center of the dikes and microcline along both walls of the dikes. Later invasion and replacement at the center and along the walls left only small zones of microcline about one-third of the way in from each wall. Microcline is almost always found in these zones; and in a few dikes where there is no quartz lens, it may be found at the center of the dike.

Microcline is relatively soluble and has been attacked by hydrothermal solutions and partially replaced by later minerals. Some individuals have been almost entirely replaced by cleavelandite and muscovite. Perthitic intergrowths of white albite and white to gray microcline were found in dike 25. They occur in a narrow zone near the top wall of the dike.

Quartz. Quartz is found in three places within the complex dikes: (1) in lenses near the center of the dikes, (2) in a small zone near the walls of the dike, and (3) rather evenly disseminated throughout the rest of the dike.

The quartz is white, milky, dull gray or, in a few instances, rose. It is always anhedral. Dikes 79 and 82 are made up almost entirely of feldspar, but grade into pure white quartz dikes or veins which stand above the rest of the rock because of greater resistance to erosion. Conchoidal fracture is most common, but a few specimens display a poor cleavage. The luster is vitreous, except for the gray quartz which has a dull luster.

Lepidolite. The lithium minerals are not very abundant. They were found in dikes 7, 11, and 86. The lepidolite was deposited in irregular zones at the center of the dikes where

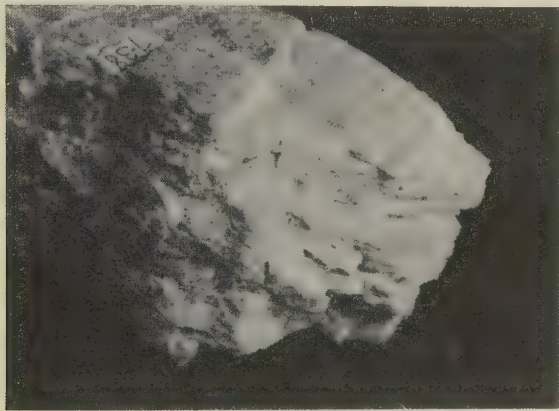


FIG. 6. Pseudomorph of albite after petalite. One-half natural size.

it is commonly associated with quartz, sericite and some cleavelandite. The mineral occurs as small plates or thin books less than 6 mm. in diameter which are rather evenly disseminated through the central part of the dikes. The plates are pale lilac in color, irregular in outline, and slightly fractured.

Petalite. Dike 86 is the only one where petalite was collected. However, pseudomorphs of albite after petalite are rather abundant in dike 7. A lens of milky quartz lies at the center of 86 and is overlain by a zone containing cleavelandite and a pseudomorph of albite after petalite. The pseudomorph, however, is absent from the zone of cleavelandite which lies immediately below the quartz lens. Number 7 has no lens of quartz at the center, but there is instead a belt of lepidolite, cleavelandite, and some sericite and quartz. This central area is both overlain and underlain by a pseudomorph of albite after petalite.

The petalite individuals are as much as 20 cm. long. They are extremely brittle and therefore highly fractured. The cleavage is good both on $c(001)$ and $o(201)$. The basal cleavage is not perfect as many textbooks describe it. The color and diaphaneity closely resemble that of pale milky quartz except along the basal fracture or cleavage planes where it is white and less translucent.

The replaced petalite resembles to some extent the original mineral. The basal cleavage lines are very distinct (Fig. 6), but traces of cleavage along $o(201)$ are poor or absent. The cleavage plates are 1 to 3 mm. thick and are always normal to the dike walls. The zones of replaced petalite lie immediately above and below the central area of lepidolite in dike 7. These zones are very irregular and are at no place more than 1.5 meters thick. Apparently the replacement was complete for no specimens of residual petalite could be found. Specimens collected from the Bridger Range closely resemble those from Londonderry in Western Australia except that the former contain more sericite and have preserved the original structures somewhat better.

Amblygonite. Although no amblygonite was collected from any of the dikes, it has been reported by Mr. Maghee to be present in dike 7.

Cleavelandite. Cleavelandite is the most abundant hydrothermal mineral present in the younger dikes. It is white to cream colored, but may be stained black by manganese oxide. The cleavelandite is subhedral with individuals varying greatly in size. The speci-

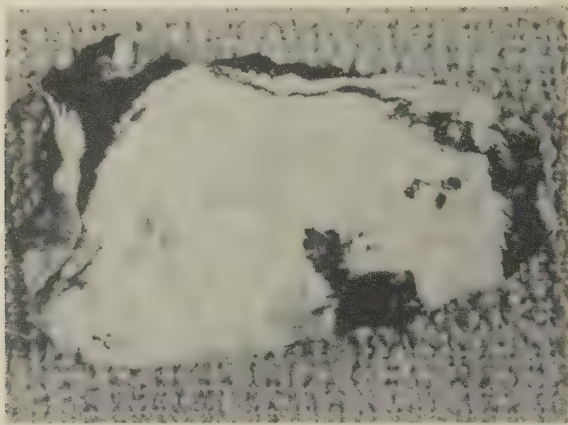


FIG. 7. Black tourmaline transecting cleavelandite. Three-fourths natural size.

mens having a sugary texture contain crystals as small as 1 mm. Several crystalline aggregates taken from dike 7 were more than 15 cm. wide. They consist of radiating tabular crystals of cleavelandite elongated parallel to the side pinacoid. Albite twinning is noticeable.

The cleavelandite occurs in irregular zones near the walls of the dike. These zones are very indefinite. A wide variety of minerals is associated with cleavelandite, including microcline, quartz, muscovite, garnet, beryl, columbite and tantalite.

Tourmaline. The ordinary black variety is the only type of tourmaline found in these dikes. It commonly occurs as elongated and striated crystals which were deposited in small veins and lenses within the dike. The tourmaline bearing solutions rose along the contact of the dikes and precipitated tourmaline crystals both in the dikes and in the schist. The mineral is subhedral and very brittle and is found replacing or cutting into quartz, microcline, cleavelandite, and schist.

Braunite. The mineral braunite always occurs in very irregular nodules surrounded by coarsely crystalline blades of greenish muscovite. The nodules in dike 85 were all found at

or near the base of a large lens or band of muscovite and cleavelandite. The mineral is dark brown to nearly black and is submetallic to earthy. The submetallic part of a specimen generally shows good cleavage in one direction, probably parallel to $p(111)$. The earthy part is browner and breaks with an uneven, slightly conchoidal fracture. Single nodules are as wide as 12 cm. but the average is about 5 cm.

Muscovite. The muscovite found in these dikes is pale green and highly fractured. Hydrothermal solutions have deposited this mineral in three distinct zones within the dikes: (1) at the contact of the dike with the country rock, (2) in lenses between the quartz lode at the center of the dike and the upper contact with the schist, and (3) in small books and flakes associated with the cleavelandite.

Muscovite is comparatively resistant to attack and is only replaced by one mineral, sericite. Small books of muscovite may be replaced along their borders, and a few specimens show small veinlets of sericite cutting entirely across books of muscovite.

Apatite. Several small aggregates of anhedral grains were identified by oil immersion methods as apatite. Such aggregates were never over 1 cm. wide, and individual grains were less than 1 mm. in diameter. These sub-rounded grains were all found in specimens collected from dike 25. However, much larger individuals are reported by Mr. Maghee to have been found in dike 86.

The mineral is dark bluish-green, translucent, and shows a sub-vitreous luster. In every specimen that contained apatite, the small grains were imbedded in a mass of white saccharoidal cleavelandite with fine flakes of muscovite and a small amount of residual pale milky quartz.

Beryl. Cleavelandite and muscovite are always associated with beryl. The beryl may occur as light green to pale blue elongated euhedral prisms imbedded in the cleavelandite zones near the center of the dike, or as aggregates of small blue green anhedral blebs in the bands of sugary cleavelandite found in the banded dikes. Some of the euhedral crystals of beryl are aquamarine and of gem quality.

The individuals vary in size from small rounded masses less than 1 mm. wide, to euhedral prisms 20 cm. in diameter. The beryl crystals cut through masses of sugary cleavelandite, but are unaltered by any of the hydrothermal solutions.

Columbite-tantalite. Both the nearly pure niobate and the nearly pure tantalate often are found in the dikes in this area. This mineral is found associated with sugary cleavelandite in a zone just above the center of the dike. The zone varies greatly both in thickness and in concentration of columbite-tantalite. Only dikes 85 and 86 contain it in considerable quantities. Specimens belonging at both ends of the isomorphous series occur in these two dikes.

Columbite is almost entirely confined to dike 85, but a few crystals were collected from 86. It crystallizes in very thin tabular crystals elongated parallel to $a(100)$. The crystals are generally less than 1 mm. thick, about 1.5 cm. wide, and 5 to 10 cm. long. The most common forms present are two prisms, brachypinacoid and macropinacoid. The mineral is also commonly in anhedral masses with quartz and cleavelandite. Chemical analyses by the Fansteel Metallurgical Corporation show that the columbite is very low in tantalum, and that one specimen from dike 86 was almost pure columbite. It is always black and displays a metallic luster. The specific gravity is 6.21, which is high for a mineral of this series so low in tantalum.

Tantalite is much more abundant than columbite, but is almost entirely limited to dike 86. A few euhedral crystals, which closely resemble those found in dike 86, were found in dike 7. Tantalite is in most cases euhedral, although a few individuals are subhedral or anhedral. Crystals of this mineral are equidimensional and may be as large as 5 cm. in diameter, but have an average width of 2 to 3 cm.

The luster is metallic and the color is generally black, but may be a medium grayish brown when weathered. The specific gravity is 7.82, which indicates a high per cent of tantalum. It has been shown (10) that in the columbite-tantalite series the specific gravity varies roughly with the amount of Ta_2O_5 .

Garnet. All of the dikes from which mineral specimens were collected contained at least a small amount of garnet. This mineral occurs as irregular, reddish brown anhedral, subhedral, or euhedral individuals with a vitreous luster. Specific gravity measurements and chemical tests indicate that the variety is spessartite.

Anhedral garnets with a dull luster were found in dike 7 where they occur in 2 to 10 cm. masses imbedded in cleavelandite. The small red and amber crystals are most commonly associated with cleavelandite, but may be found with microcline. The euhedral crystals contain both the trapezohedron and the dodecahedron. They are found cutting into microcline, evenly disseminated throughout the zones of cleavelandite, or concentrated into bands less than 2 cm. wide which dip parallel to the dip of the dike. The anhedral garnets are roughly spheroidal blebs most of which are smaller than a pin head. The garnet is very resistant to replacement and is not altered or cut by any of the other hydrothermal minerals in the specimens collected.

Chalcopyrite. A 50 cm. vein of quartz and 35 cm. zone of microcline lie at the center of dike 49. Many small irregular anhedral masses of chalcopyrite were found in this part of the dike. This mineral has in many specimens been oxidized to malachite, forming a green stain on microcline, quartz, and cleavelandite.

Supergene quartz. Cavities are very rare both in the simple and in the complex dikes. One small cavity, which was less than 3 cm. in diameter, was found in a specimen collected from dike 3. It is lined with subhedral crystals of quartz. The crystals are very poorly developed, but show a prism and rhombohedral forms. This quartz is undoubtedly supergene, having been formed after the deposition of the hydrothermal minerals.

Sericite. Sericite is commonly associated with the zones in which lepidolite, cleavelandite, columbite and tantalite are found. It was found in specimens collected from dikes 7, 85, and 86. It has been deposited along the cleavage or fracture planes of the pseudomorph of albite after petalite, in scattered flakes and grains dispersed throughout the zones of lepidolite, and in small veins cutting into and across books of muscovite. In some specimens the muscovite has been so severely attacked by sericite that only a small part of the original book remains.

Malachite. The oxidation of chalcopyrite has produced a green stain of malachite throughout dike 49, although the primary sulphide is confined to the center of the dike. A few specimens show an accumulation of malachite about 1 mm. thick.

Limonite. Limonite occurs only as small earthy masses, closely associated with chalcopyrite. It varies in color from light yellowish brown to very dark brown. The dark brown variety commonly coats chalcopyrite.

ZONING

The younger pegmatites show various degrees of hydrothermal mineralization ranging from unaltered to completely replaced dikes. The later minerals have been deposited in some dikes in distinct zones. Many of the dikes show several but no dike was found which contained all of the zones. A classification of replacement deposits follows:

1. Unreplaced dikes.
2. Cleavelandite and mica replacement (all degrees).
3. Lithium phase.

4. Columbite-tantalite and beryl phase.
5. Tourmaline phase.
6. Banded garnet phase.

UNREPLACED DIKE. No younger dikes were found which did not show at least a slight replacement along the walls by cleavelandite and muscovite. This later mineralization, however, was so negligible in several dikes that they can be considered as unreplaced. These dikes consist dominantly of white microcline and perthite with lesser amounts of pale milky quartz. The quartz is either rather evenly distributed throughout the dikes or it is concentrated in lenses and bands at the center of the dike or near the walls. The larger lenses, which may be as much as 2 meters thick, are invariably near the center. The lenses and bands near the walls are never more than 0.5 meter in thickness.

CLEAVELANDITE AND MICA REPLACEMENT. The addition of muscovite and cleavelandite may vary from a few scales and plates along the walls to an almost complete replacement of the entire dike. Mineralization obviously began along the dike walls, where microcline is replaced by white cleavelandite and coarsely crystalline muscovite. Toward the center of the replaced dike the muscovite is less abundant and more finely crystalline.

Microcline is more easily replaced by cleavelandite than is quartz, therefore, the lenses of quartz at the center and near the walls are the last parts of the original dike to disappear. Even in those dikes which are almost completely replaced, residual quartz occurs with the cleavelandite and mica near the center of the dike.

LITHIUM PHASE. Lithium minerals, including petalite, lepidolite and amblygonite, were deposited in zones at the centers of several dikes. Lepidolite is found at the center of the lithium zone, with petalite lying immediately above or below it. Where later hydrothermal mineralization has failed to replace the lens of quartz at the center of the dike, the lithium minerals were deposited directly above.

COLUMBITE-TANTALITE AND BERYL PHASE. The quartz lenses in the central part of the dikes are generally only slightly replaced. The zones between these lenses and the dike walls consist of cleavelandite and mica in many cases. It is in these zones that columbite, tantalite and beryl were deposited, mainly between the quartz lens and the hanging wall of the dike. Beryl is evenly distributed through this zone, but columbite and tantalite are found in aggregates or "pockets."

TOURMALINE PHASE. The boron-bearing solutions rose along the foot-wall contact of the dike and deposited black tourmaline in the schist, along the dike wall, and in small veins and "pockets" toward the center

of the dike. Tourmaline groups within the dikes are connected with the footwall of the dike by fractures along which the solutions passed.

BANDED GARNET PHASE. Distinct zones of banding are found in several of the dikes (Fig. 8). These bands consist chiefly of small blebs and crystals of garnet with fine flakes of mica, sugary cleavelandite, and, more rarely, splotches of greenish blue beryl. Residual pale milky quartz



FIG. 8. Specimen from younger dike showing banding. One-fourth natural size.

is also present. The zones of banding may occur in any part of the dike, but the larger ones are commonly near the footwall.

BANDING

A distinct banding of the minerals was noted in at least six of the dikes, and is especially prominent in dikes 4, 8, and 25. The bands are parallel to each other, but unequal in their thickness, which ranges from 1 mm. to 15 cm. The thickness of a single band is very uniform for several meters. Many bands are wavy, especially in a direction parallel to the strike of the dike. The dip roughly conforms to that of the dike. The zones of banding may be in any part of the dike, but are near the center in most cases. There may be as many as three of these zones separated by areas of coarsely crystalline microcline, quartz and muscovite. The banded zones do not extend throughout the entire length of every dike.

The minerals in the banded zones are very fine grained, giving the rock a saccharoidal texture. The most common minerals in the bands are cleavelandite, quartz, garnet, muscovite, and lesser amounts of tourmaline, apatite and beryl. The contact between the various bands is not sharp, but gradational. The red bands are caused by a concentration

of garnets, but many garnets are also found scattered throughout the white zones of cleavelandite.

Banding in igneous rocks has been explained as due to either gravity separation or rhythmic precipitation. Gravity separation could not have been the cause in these dikes for the minerals are not banded according to specific gravity. Bands of any type can be found in any part of a dike.

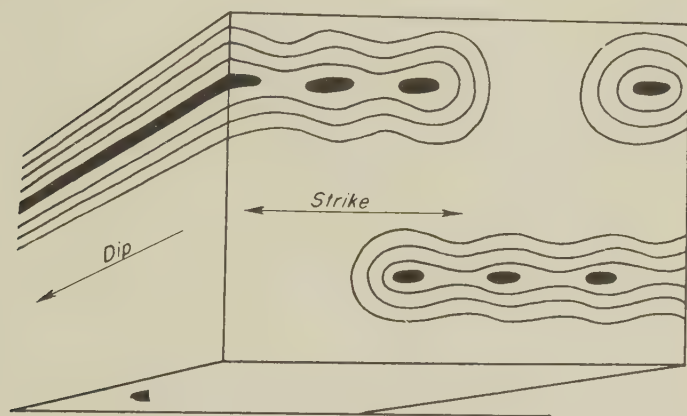


FIG. 9. Block diagram showing formation of bands concentric about finger-like openings.

The remarkable parallelism of the bands, the waviness of the bands in a direction parallel to the strike of the dike, and the less wavy character in a direction parallel to the dip of the dike indicate the development of the bands by a "rhythmic precipitation" similar to Liesegang rings (17). Hydrothermal solutions, rising along tubular or finger-like fractures elongated parallel to the dip of the dike, precipitated material in parallel bands concentric about these elongate fractures or openings. Because these openings were almost infinitely longer than wide, the bands are straight in a direction normal to the strike and irregular in a direction parallel to the strike of the dike. This view is also supported by the fact that the bands are persistent along the dip of the dike but not along its strike.

The sharpness of the bands would depend upon the physical character of the dike rock and the chemical composition of the ascending solutions. The high temperatures and pressures associated with such mineralization would also affect the physical condition of the resulting bands.

PARAGENESIS

The paragenetic relationships could not be determined for all of the minerals. Not all of the minerals were found in any single dike, so the time relationships between some minerals could not be checked. The mineralization can be roughly divided into seven stages:

1. Magmatic stage. Quartz and microcline, and perhaps a small amount of muscovite, were precipitated from the primary pegmatite magma. Because the dikes which have been subjected to hydrothermal alteration contain much more muscovite than do the unaltered dikes, the muscovite must be dominantly hydrothermal. The microcline and quartz were precipitated almost simultaneously, for every specimen shows mutual boundaries between these minerals. The muscovite is later than either the microcline or quartz.

2. Muscovitization. Intrusion of the magma was followed by replacement of part of the microcline and quartz by muscovite. Blades of muscovite transect both the microcline and quartz.

3. Lithium phase. The lithium phase is generally a late hydrothermal stage, but in these dikes the petalite is completely replaced by cleavelandite, so the lithium phase must be pre-albite in age. The minerals, lepidolite, petalite and amblygonite were deposited in a few dikes at this time.

4. Albitization. Almost every dike was partly or entirely replaced by cleavelandite. Crystals of this mineral transect microcline, quartz and muscovite, and replace large masses of petalite.

5. Other hydrothermal minerals. Because of lack of association, many minerals could not be arranged in a definite order based on time of formation. Some of these minerals were probably precipitated simultaneously and all of them transect blades of cleavelandite. They include tourmaline, apatite, beryl, garnet, columbite, tantalite and braunite.

6. Primary sulphides. Chalcopyrite is found in a vein of quartz in one dike. Because quartz is the only other mineral present, the age of the chalcopyrite cannot be determined.

7. Supergene minerals. Quartz, sericite, malachite and limonite were deposited by later supergene mineralization.

The minerals are listed in the following table as nearly as possible in the order of their formation.

Mineral	Magmatic	Hydrothermal	Supergene
Microcline	_____		
Quartz	_____		
Muscovite	_____	_____	
Lepidolite		_____	
Amblygonite		_____	
Petalite		_____	
Cleavelandite		_____	
Tourmaline		_____	
Apatite		_____	
Beryl		_____	
Garnet		_____	
Columbite		_____	
Tantalite		_____	
Braunite		_____	
Chalcopyrite		_____	
Quartz			_____
Sericite			_____
Malachite			_____
Limonite			_____

REPLACED SCHIST

North of section 27 in Hoodoo Canyon and in adjacent regions are several large areas of replaced schist. The country rock has been partly or completely replaced by later hydrothermal mineralization. The altered schist varies in color from gray to almost snow white. The areas are generally 12 to 16 meters wide, and all are less than 200 meters in length. The altered schist strikes and dips in the same direction as the original black schist. The change from completely replaced schist to unaltered material is quite abrupt, the entire transition taking place within a distance of 3 meters. The areas are bounded on all sides by unaltered hornblende schist.

Microscopic studies of thin sections of these rocks show almost complete replacement by quartz, sericite and muscovite. Several specimens contained more than 95 per cent quartz, and another showed at least 90 per cent sericite. Only slight indications of the original character of the rock were found. Almost every thin section contained grains of zircon similar to those found in the hornblende schist. Quartz is the dominant mineral in the specimens taken from the areas of replaced schist. It constitutes from 10 to 98 per cent of the rock. Sericite and quartz together in most cases make up 98 per cent of the entire rock specimen.

Because of the great extent of the replaced area in a direction parallel to the strike of the schist compared with the very limited extent normal

to the strike, and the existence of similar alteration of the country rock above and adjacent to the older dikes in sections 27 and 28, it is logical to conclude that this replacement is due to the activity of silica-rich solutions which followed the intrusion of dikes parallel to the foliation of the schist. Solutions could travel great distances in the plane of the foliation, but would be unable to penetrate the impervious layers in a direction normal to the plane of the foliation of the schist.



FIG. 10. Steeply dipping replaced schist.

The gently dipping joint system which strikes normal to the schistosity, and along which the younger dikes were intruded, is also present in the replaced schist. These joints were obviously formed after the replacement of the schist had taken place, for, if they had been present, the solutions would have traveled a greater distance in a direction normal to the strike of the schist. The replacement is probably closely associated with the intrusion of the older dikes which parallels the foliation of the schist.

HISTORY OF MINERALIZATION

The history of mineralization of this area may be summarized as follows:

1. Intrusion or extrusion of a mafic igneous magma into or upon the country rock. Microscopic examinations of thin sections of the black schist indicate a derivation from an igneous rock chemically and mineralogically similar to a diorite, or possibly a basalt. The fact that the black schist is fine grained leads one to conclude that the original igneous rock was also fine grained or perhaps aphanitic.

2. Regional metamorphism of the igneous rocks. Great pressures applied to these rocks caused a transformation of the diorite, or basalt, into a fine grained hornblende schist.

3. Intrusion of red granite. The granite is very coarsely crystalline and was probably intruded at great depth.

4. Development of the vertical jointing system. These nearly vertical joints are parallel to the foliation of the schist and extend from the schist out into the red granite and were, therefore, developed after the intrusion of the granite.

5. Intrusion of older pegmatite dikes along the vertical jointing system. The older dikes were intruded into the black schist and into the adjacent masses of coarse grained red granite. The magma soaked and forced its way through the black schist; in several places the contact between dike and schist is gradational. Considerable force also accompanied the intrusion, for in several places the foliae of the schist have been bent by the forceful intrusion of the dikes.

6. Replacement of the schist adjacent to the dikes by highly attenuated silica- and potash-rich hydrothermal solutions which deposited quartz and sericite. These solutions traveled along the vertical joints and foliation of the schist and replaced the schist rather than the minerals in the dikes.

7. Development of the second and nearly horizontal joint-set. Because the schist is replaced for a great distance in a direction parallel to the strike of the schist and for only a very short distance normal to the schist's foliation, it is apparent that these joints were developed after the replacement of the schist.

8. Intrusion of younger dikes took place along the second set of joints. The magma must have been more viscous than that which formed the older dikes because there was no soaking up of the schist by the younger dikes, and the crystals are not quite as large.

9. Hydrothermal replacement of the younger dikes. Later hydrothermal solutions replaced parts of the dikes and, in a few places, the adjacent schist.

10. Removal of the overlying country rock by erosion.

11. Supergene mineralization. This is represented by the deposition of later sericite, the oxidation of chalcopyrite to malachite and limonite, and the incipient kaolinization of feldspar.

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ORIENTED INCLUSIONS OF STAUROLITE, ZIRCON AND GARNET IN MUSCOVITE. SKATING CRYSTALS AND THEIR SIGNIFICANCE

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ABSTRACT

Microscopic crystals of staurolite, zircon and garnet included in muscovite are described. Statistical study proves that the inclusions are distributed in preferred orientations relative to the muscovite. In general, preferred orientations occur at crystallographic positions in which directions of relatively low index in the planes of contact of the inclusions and the muscovite coincide.

The included crystals are shown to have deposited from suspension upon the {001} face of the muscovite and to have moved about thereon before their burial by continued growth of the mica. The skating impetus is ascribed to the variation of interfacial surface energy with the relative orientation of the crystal faces in contact. The spontaneous, non-vectorial, movement of camphor crystals upon a water surface is analogous. The preferred orientations in the present instances express the vectorial character of crystal-surface forces, as contrasted to liquid surfaces, and mark final resting positions of relatively low interfacial energy. Experimental observations relevant to this effect are described.

INTRODUCTION

Statistical Basis of Orientation

The relative crystallographic position of two adjoining crystals is uniquely described by stating (1) a parallel pair of planes in the two crystals, and (2) the angular relation between a crystallographic direction in each of these planes. An oriented overgrowth, or oriented inter-

growth, may be defined as a position of crystallographic coincidence between crystals of unlike species with which is associated a degree of frequency greater than that of chance. The recognition, in this sense, of orientation and of randomness requires the application of a statistical method.

A statistical study is here described of the crystallographic relations of flattened staurolite, garnet and zircon crystals enclosed between the {001} cleavages of muscovite crystals. The writer is indebted to Mr. George E. Ashby of Brooklyn, New York, for opportunity to examine the specimens.

The method of study involved (1) the identification of the plane of contact of the enclosed crystals with {001} of the muscovite, and (2) the angular relation between some identifiable direction in the plane of contact and [100] in {001} of the muscovite. The latter direction was established from an interference figure in the measurement of each inclusion. The angular positions thus determined were graphed against the frequency of occurrence and the presence or absence of orientations recognized thereby.

DESCRIPTION OF INCLUSIONS

Staurolite

Golden-brown staurolite crystals averaging about 0.5 mm. in length were found in abundance embedded in muscovite from a pegmatitic zone in the Manhattan schist at 107-108th Street and Broadway, Manhattan Island, New York City. The crystals ordinarily have a lath-like habit, with the forms {010}, {110} and {101} (Figs. 1, 3). Crystals of rhomboidal habit, caused by the near suppression of {110} were noted, and long prismatic crystals extended parallel to [001] with {010} almost or entirely suppressed were not uncommon (Figs. 4, 8). Interpenetration twins on {232} were abundant. The cell dimensions of the staurolite, determined by *x*-ray rotation photographs, are as follows:

$$a_0 = 7.84, b_0 = 16.56, c_0 = 5.64 \text{ \AA.}$$

The position relative to the muscovite of 528 staurolite crystals was measured. Three different planes of attachment to {001} of the muscovite were found:

(1) 400, or 75.7 per cent, of the total number of inclusions were arranged with {010} parallel to {001} of the muscovite. The angle made by [001] of these crystals with [100] of the muscovite was measured. The statement of this angle and of the planes of attachment mentioned uniquely defines the relative crystallographic position of the two

minerals. The results of the measurements for this particular plane of attachment are represented graphically in Fig. 12. The measurements, which are accurate to $30'$, are restricted by symmetry to an angular range of 90° between the $[100]$ and $[001]$ directions of the muscovite and staurolite, respectively. The positions of orientation to be recognized from this and accompanying graphs are discussed in a following section.

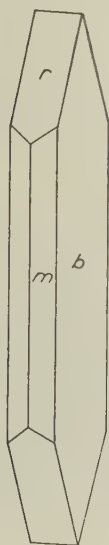


FIG. 1. Staurolite, with $b\{010\}$, $m\{110\}$ and $r\{101\}$.

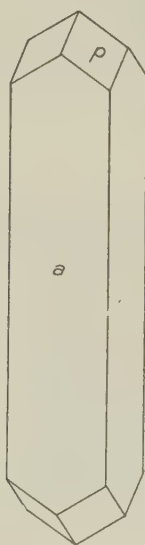


FIG. 2. Zircon, with $a\{100\}$ and $p\{111\}$.

(2) 128, or 24.3 per cent, of the total inclusions were arranged with $\{110\}$ parallel to $\{001\}$ of the muscovite (Figs. 4, 8). The angle made by $[001]$ of the inclusions with $[100]$ of the muscovite was measured. The measurements are graphically represented in Fig. 13.

(3) A few staurolite crystals were also noted which were attached by $\{101\}$ to $\{001\}$ of the muscovite. These crystals were not measured.

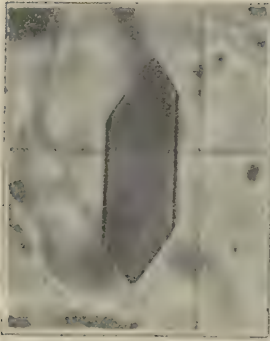


Fig. 3

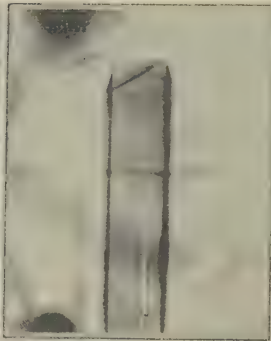


Fig. 4



Fig. 5



Fig. 6



Fig. 7



Fig. 8

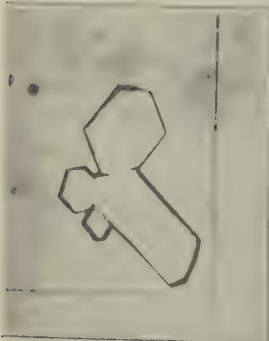


Fig. 9

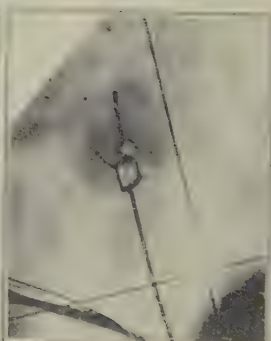


Fig. 10

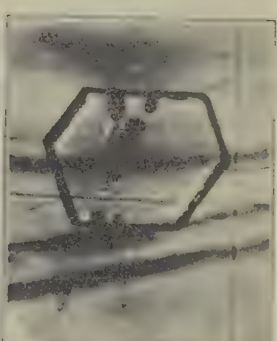


Fig. 11

(See opposite page for description to figures)

FIG. 3. Staurolite crystal flattened on {010}, with {101} and {110}.

FIG. 4. Staurolite crystal resting upon {110}, with {101} and narrow {010}.

FIG. 5. Staurolite interpenetration twin on {232}.

FIG. 6. Flattened and distorted garnet dodecahedron, with attachment of ferrous sulphate.

FIG. 7. Garnet flattened on {111} and bounded laterally by {110}.

FIG. 8. Group composed of a staurolite crystal resting on {110}, a penetration twin of staurolite tilted on side, and a narrow black prismatic crystal of unknown species.

FIG. 9. Planar group of four garnet crystals, two flattened on {110} and two flattened on {111}.

FIG. 10. Two garnet crystals impaled on a zircon prism.

FIG. 11. Garnet crystal penetrated by two zircon crystals.

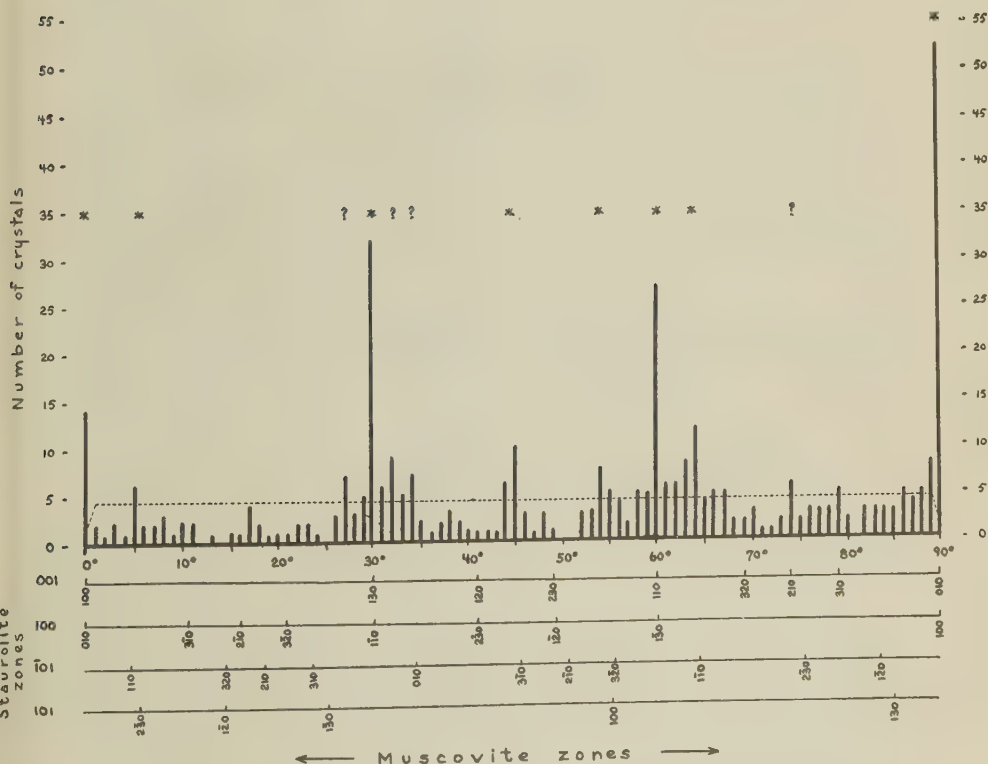


FIG. 12. Staurolite {010} upon muscovite {001}. Observed angles between staurolite [001] and muscovite [100] plotted for 400 crystals. Dotted line indicates average (theoretically random) population of graph.

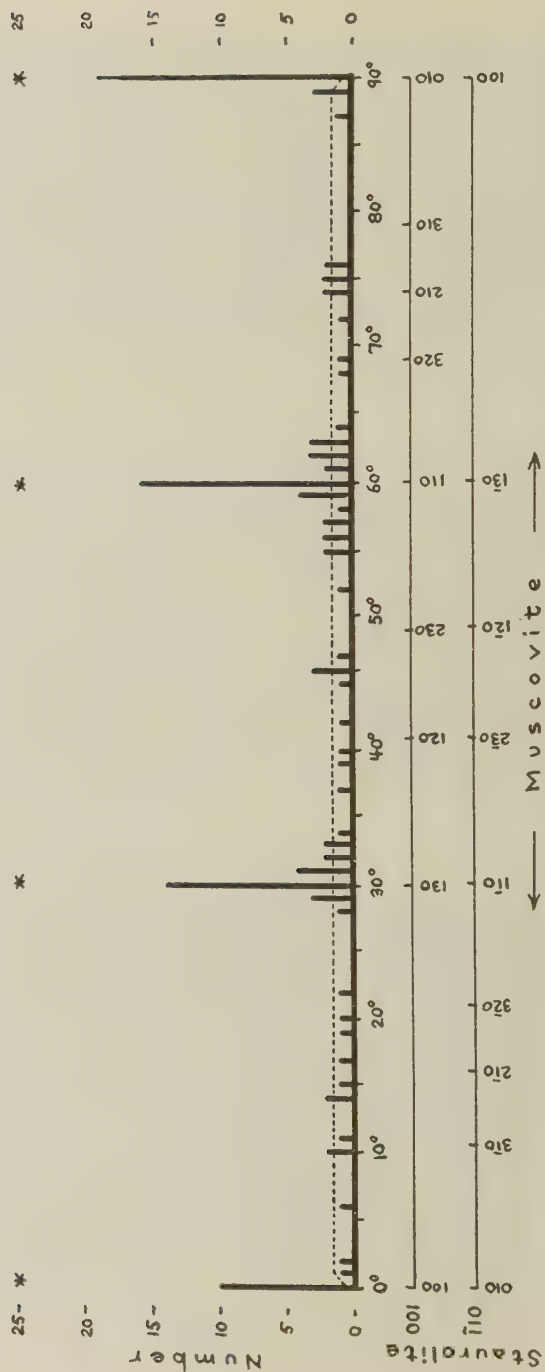


Fig. 13. Staurolite {110} upon muscovite {001}. Observed angles between staurolite {001} and muscovite [100] plotted for 128 crystals. Dotted line indicates average (theoretically random) population of graph.

Zircon

Zircon inclusions were identified in a pale greenish muscovite from a pegmatitic zone in the Manhattan schist at 176th Street between Audubon and St. Nicholas' Avenues, Manhattan Island, New York City. The crystals are long prismatic, averaging about 0.5 mm. in length, and are bounded by a prism and pyramid of different orders. The pyramid faces, which are somewhat pitted and rounded, gave interfacial angles, measured on the microscope stage, ranging between 54° and 60° . The form may be taken as $p\{111\}$, with $pp' = 56^{\circ}40'$, making the prism $a\{100\}$. This is a common habit for the species (Fig. 2). A few knee-shaped twins on $\{101\}$ were noted. In color the crystals are deep brown, sometimes with a deeper, hour-glass type of coloration beneath the faces of $\{111\}$. The cell dimensions of the zircon were not determined, since there is evidence that the crystals are altered.

All of the zircon crystals are surrounded by diffuse brown pleochroic haloes. The halo is particularly intense about minute black specks on the surface of the zircon, presumably attached crystals of a more radioactive mineral. Small, thread-like zircon prisms were often separated into a row of dash or dot-like rounded fragments. This feature, and the rough, pitted surface characteristic of the larger crystals, is doubtlessly the result of alteration.

The zircon crystals rest by a $\{100\}$ face upon $\{001\}$ of the muscovite. The angle between $[001]$ of the zircon and $[100]$ of the muscovite was measured for 92 crystals. The measurements are represented graphically in Fig. 14.

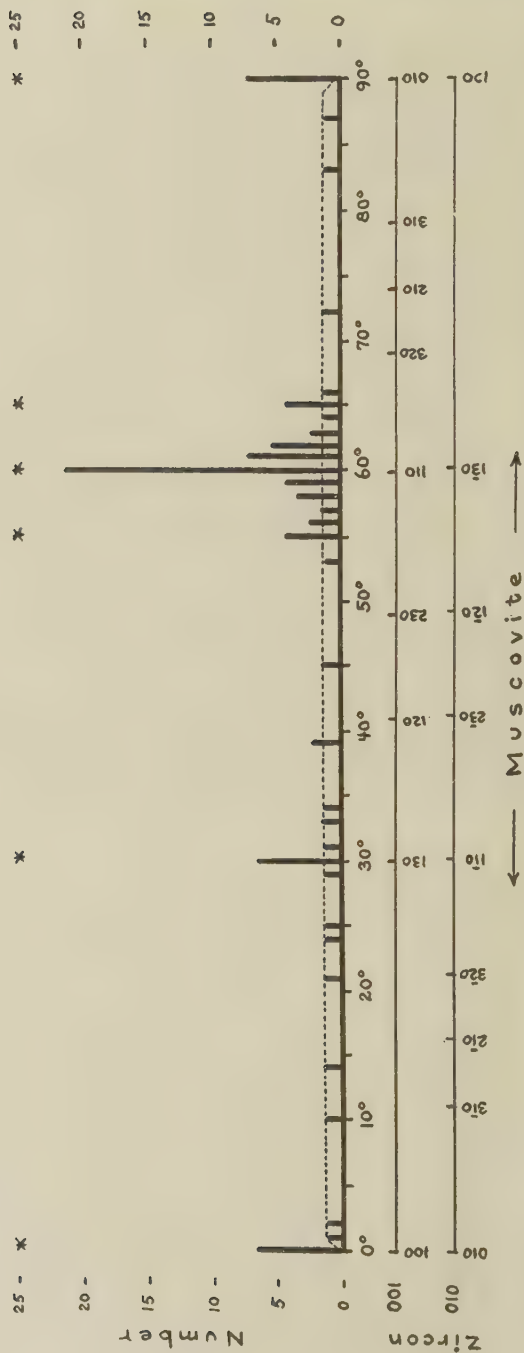


Fig. 14. Zircon {100} upon muscovite {001}. Observed angles between zircon [001] and muscovite [100] plotted for 92 crystals. Dotted line indicates average (theoretically random) population of graph.

Garnet

Flattened garnet crystals were found associated with the zircon inclusions previously described. The crystals range up to 0.5 mm. in size and are colorless, grading to pale rose in thicker individuals. Many of the garnets had a peculiar wavy appendage springing from a black spot (yellow in reflected light) on their surface (Fig. 6). The appendage has a pale green tint and is probably an iron sulphate mineral arising from the alteration of pyrite or pyrrhotite. Other garnet crystals had inclusions of zircon within them or were penetrated by needle-like zircon prisms (Figs. 10, 11). The garnet was usually radially cracked about the inclusions. The cell dimension of the garnet was determined from an x -ray rotation photograph as:

$$a_0 = 11.585 \pm 0.01 \text{ \AA}.$$

The position relative to the muscovite of 607 garnet crystals was measured. Two different planes of attachment to $\{001\}$ of the muscovite were found, as follows:

(1) 514, or 84.7 per cent, of the total number of the crystals were dodecahedra flattened on $\{110\}$ and were attached to $\{001\}$ of the muscovite by this plane (Fig. 6). The crystals were occasionally modified by $\{111\}$ or, more rarely, by an $\{hll\}$ form. Many crystals were slightly distorted by elongation on $[001]$, $[111]$ or otherwise. The angle between $[001]$ of the garnet and $[100]$ of the muscovite was measured. The measurements are represented graphically in Fig. 15.

(2) 93, or 15.4 per cent, of the crystals were flattened on $\{111\}$ and were bounded laterally by $\{110\}$, giving the crystals a hexagonal shape (Fig. 7). The reference direction used in the measurement of these crystals was a side of the hexagon, or $[\bar{1}\bar{1}2]$. The angle between this direction and $[100]$ of the muscovite was measured and the results are represented graphically in Fig. 16. The symmetry restricts the range of plotting to 30° .

Inclusions of garnet in muscovite have been reported by many previous observers,¹ but none have demonstrated a tendency for the garnet crystals to orient relative to the mica. It must be stressed that only rarely can the fact of orientation be recognized by ordinary visual inspection, as in the special case of parallelism between a number of immediately adjacent crystals. The fact of orientation or of randomness must, in general, be established by statistical investigation.

¹ For instance see Mountain, E. D., and Kent, L. E.: *Min. Mag.*, **25**, 125 (1938) and Hall, G. M.: *Am. Mineral.*, **19**, 79 (1934).

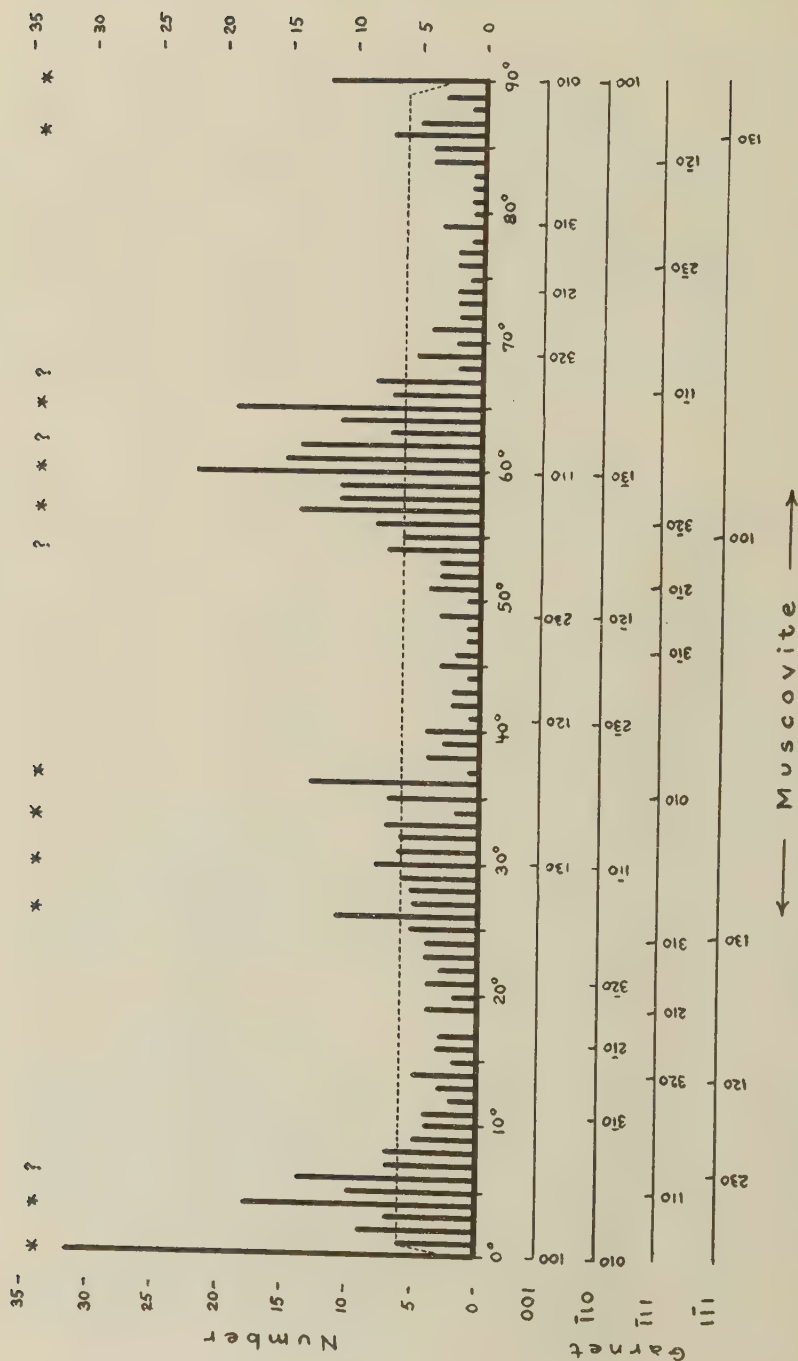


FIG. 15. Garnet {110} upon muscovite {001}. Observed angles between garnet {001} and muscovite [100] plotted for 514 crystals. Dotted line indicates average (theoretically random) population of graph.

RECOGNITION OF ORIENTATIONS. SUMMARY OF OBSERVATIONS

The measurements graphically represented in Figs. 12 to 16 state uniquely the crystallographic positions of the inclusions relative to the

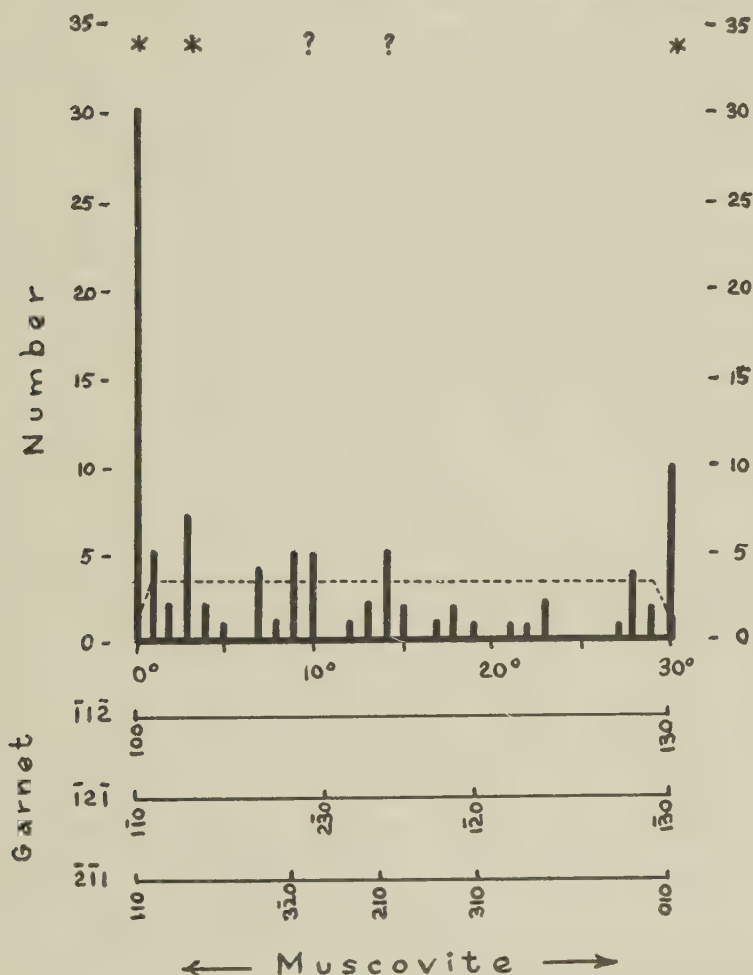


FIG. 16. Garnet {111} upon muscovite {001}. Observed angles between garnet [112] and muscovite [100] plotted for 93 crystals. Dotted line indicates average (theoretically random) population of graph.

muscovite. In general, an orientation is defined in these graphs by any position in which the statistical population is significantly greater than that expected from random distribution. The population expected from purely random distribution is indicated in the graphs by a broken line.

The recognition of orientations is, however, a matter of considerable difficulty, and is not subject to any generality of treatment. It may be noted that the actual position of an orientation may fall between the arbitrary reference divisions on the graphs, causing a distribution of observations about that position with consequent loss of definition. Closely spaced orientations also suffer loss of definition. Such positions can not be located more precisely by any statistical test, and their definition can be increased only by increased refinement of measurement and plotting. Also it is questionable whether orientations can be recognized with any certainty in regions of the graphs in which the population of sequential positions of reference is less than 3 or 4, regardless of the total number of observations. The low population (group number) prohibits an estimation of the validity of such orientations by statistical methods, such as the χ^2 "goodness-of-fit" test applied by H. Winchell² to the analysis of petrofabric diagrams. Uncertainty also arises as to the significance of positions of relatively high population that occur adjacent to major orientations. Positions of this nature doubtlessly contain a proportion, at least, of observations distributed through error of measurement about the major orientation.

The positions on the graphs whose population is considered to be significantly greater than that of chance distribution are summarized in Table 1. A few orientations of doubtful validity are included. Both the doubtful and the certain orientations are also indicated in the graphs, by question marks or asterisks.

Correlation Between Orientations and Coincidence of Directions of Low Index

The successive coincidences between directions of relatively low index in the contact planes of the inclusions and the muscovite, as the former are rotated upon the latter, are represented in the several graphs. In illustration, the direction [001] in {010} of staurolite coincides with [130] in {001} of muscovite, when the reference directions used in the measurement of the two minerals, staurolite [001] and muscovite [100], make an angle of 30°. It should be noted, however, that at any angular position of the reference directions an infinite number of directions in the contact planes of the two minerals coincide. Only a small selection of coincidences of relatively low index are here given.

Major orientations are found to occur at angular positions in which directions of relatively low index in the planes of contact of the two minerals coincide. This significant circumstance was first noted in a study of tourmaline inclusions in muscovite.³

² Winchell, H.: *Am. Mineral.*, **22**, 15 (1937).

³ Frondel, C.: *Am. Mineral.*, **21**, 777 (1936).

A position of orientation and the frequency thereof, however, can not be quantitatively connected with some particular coincidence of this kind. It is obvious that the graphs are ambiguous in that many coincidences of different directions overlap at any angular position of

TABLE 1. SUMMARY OF OBSERVED ORIENTATIONS

Mineral	Contact plane with {001} of muscovite	Observed angle between stated direction and [100] of muscovite	Per cent of total number of crystals attached by stated contact plane	Mineral	Contact plane with {001} of muscovite	Observed angle between stated direction and [100] of muscovite	Per cent of total number of crystals attached by stated contact plane
Staurolite	{010}	[001] 0°	3.5	Garnet	{110}	[001] 0°	6.2
		5°	1.5			4°	3.5
		27°?	1.7			6°?	2.7
		30°	8.0			26°	2.1
		32°?	2.2			30°	1.5
		34°?	1.7			33°	1.4
		45°	4.0			36°	2.5
		54°	3.0			54°?	1.4
		60°	6.7			57°	2.7
		64°	3.7			60°	4.3
		74°?	1.5			62°?	2.7
Staurolite	{110}	[001] 0°	7.8	Garnet	{111}	65°	3.7
		30°	10.9			67°?	1.5
		60°	12.5			86°?	1.5
		90°	14.8			90°	2.3
Zircon	{100}	[001] 0°	6.5			[112] 0°	32.3
		30°	6.5			3°	7.5
		55°	4.3			10°	5.4
		60°	22.3			14°	5.4
		65°	4.3			30°	10.8
		90°	7.6				

orientation, and the contribution of each of these to the orientation is not apparent. Evidence of this ambiguity is found in that the equivalent + and - positions of some particular coincidence which occur at different angular positions in the graphs have not equal frequency. Thus in Fig. 12, it is seen that at an angular position of 15° that staurolite $[\bar{1}01]$ is parallel to muscovite $[320]$ with a population of 1, while at an angular position of 56° the equivalent directions of opposite sign, staurolite $[\bar{1}01]$ and muscovite $[3\bar{2}0]$, are again parallel, but with a population of

4. The identification of an orientation-frequency with a particular coincidence requires a knowledge of the general relation between the two crystals which finds expression in the orientation phenomenon itself. This situation and its implications are outlined more fully in a later section.

It is considered that all of the graphs would define additional orientations if the number of observations was increased. In their present stage of development there is no conclusive evidence that the occurrences at any position are entirely of chance distribution.

MODE OF EMPLACEMENT OF THE INCLUSIONS

Two theories of origin of the inclusions may be suggested. The crystals now present as inclusions originally may have been freely suspended in a solution that was in contact with growing crystals of muscovite. The suspended crystals came into contact with the {001} faces of the muscovite, through gravitational settling or current action, became attached thereto, and were then buried by the continued growth of the mica. On the other hand, the garnet, staurolite and zircon crystals may have nucleated and crystallized directly upon the surface of the mica and were then buried. The characters of the inclusions which bear on their origin are discussed below:

(1) Edge and Corner Attachment. The penetration twins of staurolite, and groups of two or more intersecting garnet, zircon or staurolite crystals rest upon {001} of the mica by the touching of corners and edges of the aggregate and not by plane faces (Figs. 5, 8). Attachment in this way suggests attachment by mechanical settling-out. Direct crystallization of the crystals upon the surface of the mica would result in attachment by a plane face.

(2) Impaled Crystals. Conclusive evidence of the prior existence in the solution of suspended crystals is found in the occurrence of garnets impaled on needle-like prisms of zircon (Fig. 10). Other garnets had small inclusions of zircon, or had broken stubs of zircon prisms extending from their surface (Fig. 11). These intergrowths must have been preformed.

(3) Damaged Crystals. Staurolite and garnet crystals with their edges chipped or nicked were occasionally noted, as were broken zircon crystals. While the damage may have been inflicted through the contact of some body with the crystals while they were attached to and exposed on the surface of the mica, it seems more likely that chipping would result from jostling about in suspension or by impact with the mica surface.

(4). Bunched Crystals. Aggregates of 2, 3 or more staurolite or garnet crystals were noted which were attached to the mica by a face and touched laterally but did not interpenetrate (Figs. 8, 9). Also, the grouped crystals often were not all attached to the muscovite by the same plane (Fig. 9). These occurrences are inconsistent with an origin by direct crystallization upon the mica. Surface crystallization would favor scattered, isolated crystals, since the inception and growth of a crystal impoverishes the solution in its neighborhood and thereby acts against the formation of immediately adjoining nuclei. On the other hand, the bunches themselves can not have been preformed, since they lack cohesion

as a unit and, also, are arranged in a common plane. These planar aggregates seem best explained by the assumption that the individuals composing them had slid about on the surface of the mica until their movement was stopped by contact with another crystal, or otherwise, with the building up of a log-jam.

(5). Restrictions in Kind of Contact Surfaces. Only those planes which are present as bounding faces on the crystals occur as contact surfaces with $\{001\}$ on the mica. This is evidence for mechanical settling-out, insofar that direct crystallization upon the mica surface would not be limited in this way.

(6). Variation in Plane of Flattening. The plane of flattening varies somewhat according to the plane of attachment to the mica (compare Figs. 6 and 7 of garnet). This variation, and the occurrence of flattening itself, would not be expected if the crystals had been entirely preformed, by free growth during suspension in a solution. Crystallization directly upon the surface of the mica would satisfy the observations, since artificially overgrown crystals tend to become flattened parallel to the plane of attachment. However, the flattening can also be explained on the assumption that the crystals fell with a particular face upon the mica and still continued to grow, becoming flattened thereby.

It is considered that the observations described above force the conclusion that the crystals were preformed and had been mechanically attached to and then enclosed by the muscovite. The growth of the crystals probably continued after their attachment to the mica and up to the time of their burial by the simultaneously growing mica.

The manner in which the various orientations were impressed on the crystals now remains to be explained. Since the circumstances of incidence of the suspended crystals were without directional qualities, the observed orientations must have been assumed after the attachment of the crystals through some control exerted or participated in by the muscovite.

FACTORS CONTROLLING ORIENTATION. SKATING CRYSTALS

If ether vapor is brought into contact with a smooth surface of water, vigorous movements and currents are spontaneously set up in the latter. Ether markedly lowers the surface tension of water but the lowering does not take place uniformly over the water surface, so that liquid is drawn surficially from places of low surface tension to those of a higher one until equilibrium is reached. Similarly, camphor lowers the surface tension of water from approximately 70 to 21 dynes. If a small piece of solid camphor is dropped upon a clean surface of water it slowly dissolves and, at the same time, rapidly moves about under the impetus of local inequalities in surface tension. This movement is, of course, non-vectorial.

A plane crystalline surface that has come into contact with another crystalline surface is subject to similar influences. An essential difference from liquid surfaces exists, however, in that crystals are vectorial structures and the properties of their surfaces vary with direction therein.

Accordingly, at the contact of two plane crystalline surfaces, the interfacial surface energy must vary with the relative position of orientation of the two crystals. Only one position of orientation, together with any equivalent positions fixed by symmetry, is that of minimum interfacial energy. This particular position, for reasons pointed out elsewhere by the writer,⁴ is that of most stable mutual coincidence of the two crystals. Crystals in contact, if given freedom of choice, would assume this special orientation. However, under certain circumstances described below, an infinite range of orientations must be expected.

It is assumed that a crystal freely suspended in a medium is brought randomly upon a plane crystalline surface and can move thereon in rotatory fashion under an original impetus. During the rotation of the crystal the interfacial surface energy will continuously increase and decrease in value, according to the relative crystallographic position of the two individuals. As the original impetus decreases, a point will be reached in which the kinetic energy is insufficient to push the crystal over some position of relatively high interfacial energy. The movements of the skating crystal would then be constrained to a particular range of interfacial energies, or orientations, and become more and more vectorial. The final position of rest will be that of minimum interfacial energy within this range. This position of orientation is seen to be not necessarily that of least interfacial energy between the contact planes of the two species of crystals. The various positions of orientation thus fixed express a frequency analysis of the relation between interfacial surface energy and orientation. The orientations observed between the garnet and other inclusions in the muscovite are believed to be of this origin. While an original impetus is assumed, the crystals probably move about at least in part under the impetus of the surface forces, as with camphor.

Some Relevant Observations

The reality of the orienting mechanism described above has been demonstrated experimentally. If small octahedra of alum are suspended by agitation in a saturated solution of alum and are allowed to come into contact with a large octahedral surface of alum exposed in the solution, it is found that the small crystals become attached to the larger surface. This attachment is not at random positions. The measurements of Schaskolsky and Schubnikov,⁵ who devised the experiments to test the earlier observations of Gaubert⁶ on lead nitrate, and of Laemmlein⁷ on

⁴ Frondel, C.: *Am. Jour. Sci.*, **30**, 51 (1935).

⁵ Schaskolsky, M., and Schubnikov, A.: *Zeits. Krist.*, **85**, 1 (1933).

⁶ Gaubert, P.: *Bull. Soc. Min.*, **19**, 431 (1896).

⁷ Laemmlein, G. G.: *C. R. Acad. Sc. U.S.S.R.*, 709 (1930).

quartz, proved that the superposed alum crystals are distributed among definite positions of orientation. These authors also express the view that the small alum crystals after falling randomly upon the larger alum surface spontaneously rotated to the observed positions of orientation.

The effects described above are a direct extension of the well established fact that large crystals may grow by the direct attachment of crystals of colloidal size to their surface. The observations of Walmsley⁸ on the direct linking together of ultra-microscopic dodecahedra of cadmium oxide dispersed in air to form large aggregate single crystals afford a particularly convincing illustration. In general, the orienting effect is enhanced among crystals in the colloidal range of sizes because the mass of the crystals is small relative to the surface forces which control the process.

A Structure-Analysis Implication of Orientation

An interesting implication may be remarked. Inasmuch as the orienting tendency is an expression of the arrangement, spacing and bonding of the structure-units which compose the contact surfaces, then the orientation-frequencies, which express the variation of some structure-determined factor, presumably surface energy, with direction, should lead to the analysis of the crystal structures.

The periodicities in the contact surface of the randomly impinging crystals analyze the periodicities in the supporting crystal surface in the same sense that the periodicities in an impinging heterogeneous beam of x -rays analyze the periodicities of a crystal. The orientation graphs may be likened to powder diffraction patterns, in which the positions and intensities of reflection are represented by the positions and frequencies of orientation.

The indexing of an orientation graph could proceed by means of coincidence tables, such as are graphically represented in the figures. Assuming that the structure of one of the minerals is known, then the relative position and importance (in some structural regard) of crystallographic directions in the contact surface or surfaces of the unknown crystal may be found in a cut and try way similar in principle to the indexing of an x -ray powder photograph. It is necessary in this, however, to first know the general relation obtaining between structure and position-frequency which finds expression in the orientation itself, that is, some equivalent of the Bragg equation. Efforts to find such a relation by comparing packing densities along assumed shared directions in the inclusions and in the muscovite were unsuccessful.

⁸ Walmsley, H. P.: *Proc. Phys. Soc. London*, **40**, 7 (1928).

EXPERIMENTAL INVESTIGATION OF SKATING CRYSTALS

Two experimental techniques were devised to investigate the control exerted by a plane crystalline surface on the orientation of mechanically superdeposited crystals.

Adherence Angle Technique

This technique is based on the von Buzagh method of measuring the adherence angle of solid particles resting upon a plane surface in a solution.⁹ A von Buzagh apparatus was obtained¹⁰ and was modified by the writer by the addition of a graduated rotating stage to the tilting stage. The device as modified permitted the measurement, by rotation of the stage in successive experiments, of the angle of slip along various directions in a supporting plane crystalline surface. A cleavage sheet of muscovite was used for the supporting surface. The idea was that the angle of slip would vary with the orientation of the muscovite, and that this angle would be related to the structural make-up of the mica along the direction of slip.

Experiments were made using fine powders of glass, staurolite and quartz. The angle of slip, however, was found to vary erratically, and duplicable measurements could not be obtained at any fixed orientation. The principal difficulty was in obtaining particles of the proper size. Control of this factor, for reasons described by von Buzagh, is essential to the application of the adherence angle method. Spherical glass or metal beads of the proper size would probably afford a fair test of the idea.

Sedimentation Technique

A plane crystalline surface was placed in a saturated solution of a given salt, and minute crystals of that salt were allowed to settle out thereon. The crystallographic positions of the superposed crystals relative to the supporting crystal were then measured and graphed.

An extensive series of experiments were undertaken in which minute octahedra of alum were allowed to settle out upon a cleavage sheet of muscovite immersed in a saturated solution of alum. The results of the best of these experiments are shown in Fig. 17. It is considered that the graph does not define any well-marked tendency for orientation.

⁹ von Buzagh, A.: *Kolloid Zeits.*, **47**, 370 (1929); **51**, 230 (1930); **52**, 46 (1930).

¹⁰ Through the courtesy of Prof. Ernst H. Hauser, Department of Colloid Chemistry, Massachusetts Institute of Technology.

Experiments were also made in which KClO_3 crystals were deposited upon muscovite, and in which minute cleavage cubes of galena were settled out from water upon muscovite and upon gypsum. The measurements made with these substances did not prove any undoubted

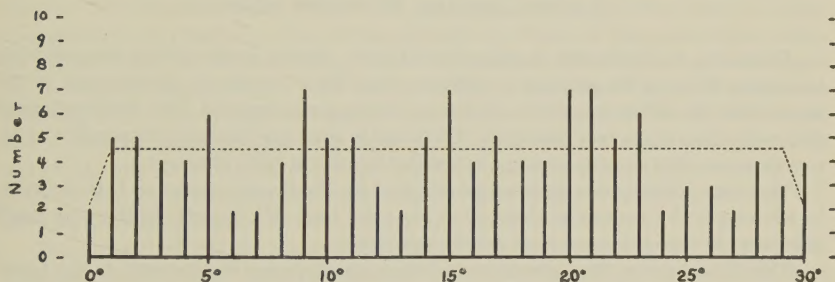


FIG. 17. Alum $\{111\}$ upon muscovite $\{001\}$. Observed angles between alum $[110]$ and muscovite $[100]$ plotted for 131 crystals. Dotted line indicates average (theoretically random) population of graph.

tendency for orientation. It is felt, however, that these experiments and those with alum mentioned above may have been largely prejudiced by errors introduced during the manipulation of the supporting crystal and by errors of measurement.

NOTES AND NEWS

A SIMPLE DICHROSCOPE

NEWMAN W. THIBAUT,

Norton Company, Worcester, Mass.

Dichroism, or pleochroism in minerals and gems, may be observed with the polarizing microscope by using the polarizer or analyzer alone. Upon rotation of the specimen, or the nicol prism, the different colors or shades are successively observed. The disadvantage of this method lies in the fact that slight differences in color are difficult or impossible to detect since one color must be kept in mind while the other is being observed.

The usual calcite prism dichroscope designed by Haidinger¹ overcomes this objection by allowing both colors to be observed at the same time side by side. In this way small differences in absorption are more readily perceived.

The advantages of the dichroscope and the microscope are incorporated in the Leiss² dichroscope ocular which also employs a calcite prism. It was intended for the observation of the pleochroism of small fragments in rock sections. In using this ocular, both polarizer and analyzer must be removed, and because of the partial polarization caused by the sub-stage mirror, direct light is to be preferred.

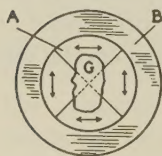


FIG. 1a

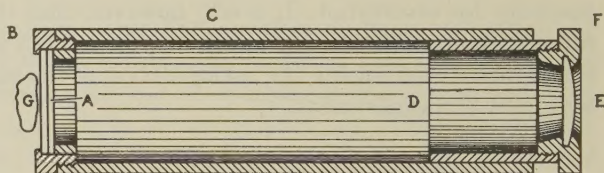


FIG. 1b

FIG. 1a, mounted disc of reoriented Polaroid, and FIG. 1b, longitudinal section through Polaroid dichroscope. A, Polaroid film mounted in collar, B; C, body tube; E, lens mounted in collar, F; D, lens tube; G, substance being examined.

Recently the remarkable dichroic properties of the sulphate of iodo-quinine, herapathite, or related substances have been utilized commercially in the production of substances giving nearly perfect plane polarized light by absorption.³ Bernauer's Bernotar filters made by Zeiss, Marks Polarizing Plates, and Polaroid are three such substances. For the device about to be described, Type II Polaroid is by far the best adapted for use, since the herapathite crystals are dispersed in a cellulosic base which may easily be cut.

The usual Type II Polaroid film may be utilized with an ordinary microscope for the observation of pleochroism in a manner analogous to the use of a single nicol prism mentioned above. Or with larger specimens of minerals, or gems, little or no magnification may be necessary. The disadvantages are the same, one of the two pleochroic colors must be kept in mind while the other is being observed.

The device to be described is apparently new, and allows both colors to be observed side by side at the same time. The essential feature consists of a circular piece of Polaroid

¹ Haidinger, W., Ueber den Pleochroismus der Krystalle: *Pogg. Ann.*, **65**, 1-30 (1845).

² Leiss, C., Ocular-Dichroscop für Mikroskope: *Neues Jahrb.*, **92**, 1897 (II).

³ Grabau, M., Polarized light enters the world of everyday life: *Jour. Applied Physics*, **9**, 215-225 (1938).

divided into quadrants. The direction of vibration of the transmitted vector in each quadrant is perpendicular to that in the immediately adjacent quadrant. This will be clear from the examination of Fig. 1*a* in which the arrows indicate the direction of vibration of the ray transmitted by the Polaroid of each quadrant. At the present time this orientation is obtained by very carefully cutting and reassembling pieces of Polaroid which are then mounted between glass. Figure 1*a* shows the orientation preferred by the author, but other arrangements are possible so long as the vibration directions of the transmitted vectors are perpendicular as outlined above. For the examination of mineral and gem specimens the reoriented Polaroid may be used with or without a small hand lens, but a permanent mounting in the form of a dichroscope is to be preferred. In Fig. 1*b* the reoriented Polaroid film is mounted between strain-free glass (A). This is held in a metal collar (B) which screws into one end of a tube (C). A $2\frac{1}{2}$ or 3 times magnifying lens (E) is mounted in a collar (F) which screws into a small tube (D). The latter forms a friction fit with tube (C) allowing the magnifying lens to focus sharply upon the Polaroid film.

The device is used in the same manner as the calcite prism dichroscope. The specimen to be examined (G, Fig. 1) is placed in front of the Polaroid film (A) and is observed through lens (E). If the substance is more than very weakly pleochroic, rotation of the instrument relative to the specimen will result in some position in which adjacent quadrants of the Polaroid film are of different colors or shades while opposite quadrants are similar in color. Maximum difference will be shown when the vibration directions of the specimen are parallel to the direction of vibration of the transmitted vectors in adjacent Polaroid quadrants.

One advantage of this device is the ease and small expense with which the reoriented Polaroid disc can be made by the user. Another advantage is the easier and more certain determination of pleochroism in small gem stones cut from weakly dichroic or pleochroic minerals. The following very brief list gives an indication of results to be expected from observations on faceted stones:

Stone	Locality	Weight in carats	Color	Dichroism	Degree of dichroism observed
Synthetic ruby	—	1.05	bright red	pink to deep red	very distinct
Smoky quartz	—	1.26	gray brown	light to medium gray brown	distinct
Amethyst	Uruguay	.84	lavender	very light to medium lavender	distinct
Tourmaline	Africa	1.18	pink	light to medium pink	distinct
Tourmaline	Maine	.59	light green	light green to light olive green	distinct
Sapphire	Montana	.25	light blue	light greenish blue to light purplish blue	less distinct
Zircon	Indo-China	.67	light blue	light blue to nearly colorless	less distinct
Emerald	Colombia	.70	bright green	bright green to olive green	less distinct
Aquamarine	Maine	.39	very pale blue	pale blue to colorless	faint

One disadvantage of the device is related to the absorption characteristics of Polaroid film which shows a slight residual color by transmitted light. This feature is discussed in detail by Grabau⁴ who shows the transmission to be nearly constant between 4800 and 6700 Å, the range within which the eye is most sensitive. It is possible to compensate for a part of the differential absorption outside this range by the use of certain Jena optical glass color filters, but this is not thought to be necessary because of the satisfactory results obtained with Type II Polaroid alone. Another possible objection is that the color seen in each quadrant is produced by light passing through different parts of the mineral or cut stone. This is of no practical importance, however, since four pieces of Polaroid are in contact, and by slightly moving the dichroscope in relation to the mineral during observation, any effects due to reflection from facets, or unequal thickness, are quickly observed.

For use with the microscope in a manner similar to the Leiss dichroscope ocular, the reoriented Polaroid disc described above could be mounted in the cross-hair position in a low power Huygens ocular, or set into a plate to be inserted beneath a Ramsden or positive ocular. As stated in connection with the Leiss ocular, both polarizer and analyzer must be removed, and the light should be received directly instead of from the mirror.

⁴ Grabau, M., The optical properties of Polaroid for visible light: *Jour. Opt. Soc. Amer.*, **27**, 420-424 (1937).

BOOK REVIEW

THE GEOLOGY OF THE ANORTHOSITES OF THE MINNESOTA COAST OF LAKE SUPERIOR. FRANK F. GROUT AND GEORGE M. SCHWARTZ. *Bull.* **28**, Minnesota Geological Survey, University of Minnesota Press, 1939, 119 pp., 49 figs., 6 pls.

This report is based primarily on a detailed study of the geology of an area of about 200 square miles along the north shore of Lake Superior. The rocks comprise a series of Keweenaw volcanics, mostly basalts but with rhyolites and minor sediments, the whole intruded by diabase sills. With the latter there is locally closely associated a red granite. They dip about 10° SE and overlie the great differentiated Duluth gabbroic sheet, forming part of the north limb of the Lake Superior geosyncline.

The anorthosite of the area has proven to have a rather peculiar origin. It occurs widely distributed in the olivine diabase sills, as fragments varying in size from single plagioclase crystals up to over a quarter of a mile across. Most are a few yards across. Subordinate amounts of other rocks, gabbros, rhyolite, and basalt are locally associated but are not abundant. Anorthosite fragments are also found in red granite and in amygdaloidal basalt flows. They are interpreted as picked up by the magma during its rise from the depths and are referred to a probable source in the anorthosite facies of the Duluth gabbro sheet, which dips at depth beneath the area. Many anorthosite fragments are near the top of the diabase sheet and some are near the bottom. The authors conclude that the specific gravities of anorthosite, if included without being much heated, would be heavier than the liquid diabase, but if immersed for a long time, or immersed in the depths where all rocks are hot, might be lighter. This is an interesting sidelight on the much mooted problem of whether early plagioclase crystals sink or float in diabasic magma. Data are given on the composition of the plagioclases of diabase and of anorthosite.

A short chapter is devoted to possible economic uses of the anorthosite fragments.

The report sheds little light on the general problem of the origin of anorthosite as such but gives an excellent and detailed description of a most unusual development of a somewhat perplexing petrologic phenomenon.

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